FACILITATION AND INHIBITION

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By

THOS. N. JENKINS, A.M.

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Submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy, in the faculty of Philosophy, Columbia University.

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R. S. WOODWORTH, EDITOR

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SYNOPSIS

Reaction-times were measured for five subjects for the appearance and disappearance of light accompanied by a simultaneous but irregular presentation and removal of sound. The energic and frequency characteristics of the stimuli were known.

The auditory stimulus was produced by an oscillator having wood core inductances and having a frequency range of 8—50000. A small amount of power was taken off, amplified, and finally filtered to eliminate harmonics before actuating the receivers. The receivers were thermophonic capsules (inserted in the meatus of the ear) having thermoelements of platinum wire .0018 cm. in diameter.

The visual stimulus was produced by a monochromatic illuminator consisting of a constant deviation prism, wave-length drum, and collimator and analyzer tubes of large diameter containing a series of diaphragms to absorb stray light. Measurements of the intensity of the light at the subject's eye were made with a radiometric apparatus consisting of a vacuum thermopile, Thomson galvanometer, and a radiation standard.

The exposure apparatus was a noiseless pendulum.

A mechanism was provided for the control of the length of the intervals between reactions and the order of presentation and removal of the stimuli.

The chronoscope was operated by a motor delivering its power through a belted transmission containing a friction clutch of polished brass. With this arrangement the power delivered to the chronoscope was independent of the speed of the motor.

The subjects reacted alternately to the presentation and removal of light. No special preparatory signal was used. The auditory stimulus appeared and disappeared irregularly. This procedure gave eight different combinations of stimuli: (1) light and sound, (2) darkness and quiet, (3) light and quiet, (4) darkness and sound, (5) light with the tonal stimulus continuing without change, (6) light with a continuance of quiet, (7) darkness with the tonal stimulus continuing without change, (8) darkness with a continuance of quiet.

Results: Reaction-times to darkness tend to be shorter than those to light, but the onset of quiet facilitates less than that of sound. Reaction-times for both light and darkness are shorter when the sound continues without change. There is a small negative correlation between the average and the amount of skewness. There tended to be a low negative correlation between the coefficient of variation and skewness, and a significant negative correlation between the average and the coefficient of variation.

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Facilitation and Inhibition

SECTION I

The Problem

The present study is an attempt by a more refined method and technique than usual to determine the effect of an irregular presentation and removal of sound upon reaction-time to the appearance and disappearance of light. An endeavor is made to so adjust physical conditions and the mode of procedure that an objective check, other than the verbal report of the subject, may be obtained as to whether the reactor actually succeeds in following instructions by reacting to a specified stimulus of a constellation of stimuli. Furthermore, the adjustmental or *volitional factor* may be different for some modes of stimulation than for others, so an attempt was made to equalize the effects of possible variability in the strength of the reactor's adjustment for the reception of and response to a specific stimulus in a stimulus set of several stimuli of different modes. The necessary conditions and means of control will be fully discussed under the section on Apparatus and Method.[1]

[1] It gives the writer sincere pleasure to acknowledge at this time his debt of gratitude to Prof. A. T. Poffenberger for valuable criticism, sympathetic interest, and encouragement, and to Prof. R. S. Woodworth for his criticisms of the early formulation of the problem.

SECTION II

Historical Summary

The problem of facilitation and inhibition as an object of experimental research is not new. Physiologists have been especially interested in it on the reflex level, and have evolved a fairly well standardized terminology for the different forms of reflex facilitation and inhibition, such as, reciprocal inhibition, summation, induction, and exaltation or rebound. A good example of reflex re-enforcement and inhibition is to be found in the case of the patellar reflex. Bowditch[2] and Warren found that auditory, visual, and tactual stimuli preceding the tendon blow by .1 to .5 sec. re-enforce the knee-jerk, but such stimuli preceding the blow by .5 to 1.0 sec. inhibit the reflex. Exner[3] found that cortical stimulation if given not more than 3 sec. before subliminal stimulation of the skin on the foot of a rabbit, renders the cutaneous stimulation effective. If both are subliminal, each makes the other effective provided the interval between them is not over .125 sec. Similarly, for the dog, cortical and cutaneous stimulation re-enforce when both are subliminal, if the interval between them is not greater than .6 sec.

On the conscious level we find such terms as "mental set" to designate a type of adjustment which facilitates acts preparatory to, and inhibits acts which do not lead to a consummatory response. In this same category might be mentioned the phenomena of interference in learning and memorizing designated by different writers by such terms as associative and reproductive inhibition, retro-active inhibition, effectual and generative inhibition (Müller & Pilzecker), antero- and retro-grade detraction (Poppelreuter). The so-called supressions of Freud are good examples of permanent interference.

There are certain forms of facilitation and inhibition which may and usually do accompany voluntary adjustments, and which occur in spite of voluntary control, and which may often and perhaps usually do occur without the subject being aware of them. Within this class we can conveniently place the so-called sensory facilitations and inhibitions. Retinal

[2] Bowditch and Warren, *Jour. Physiol.*, 9:60 (1890).
[3] Exner, *Arch. f. d. ges. Physiol.*, 28:495 (1882).

rivalry, monocular and binocular, is a fair example of sensory inhibition that the subject is vividly aware of, and has been the subject of a research by Breese (2). Some of the more subtle forms of sensory inhibition have been investigated by Jacobson (18), Heymans (17), Revesz (24), Spencer (26), and also incidentally by Cobb, Ferree, and Johnson. Revesz found that the threshold for spectral colors is proportional to the brightness of a surrounding field of white light. Heymans, working with colors in 1899, stated a "general law of inhibition" formulated as follows:

$$T_A = T_o + kA$$

where T_o is the simple threshold of a given stimulus, T_A is the threshold raised by the presence of a second stimulus of intensity A, and k is a coefficient of inhibition which differs for different modes and different subjects. Spencer determined the inhibiting effect of one white light upon the perception of another in the case of the white rat, and found his results in general agreement with Heymans' law. He did not measure the intensities of his lights, but determined their relative intensities by the use of episcotisters. Heymans says Weber's law is a special case of the general law of inhibition; i.e., the perception of a difference is inhibited by the intensity of the stimuli compared. Heymans seems to assume all along that this inhibition is central in origin, and even tries to explain the upper and lower limits of Weber's law as due to inhibition. The truth of this theory is doubtful in view of present physiological data concerning the relation of receptor stimulation to neural excitation. The most recent work on the electrical response of the optic nerve to retinal stimulation by light corroborates the work of previous investigators in asserting that the logarithmic relation holds between intensity of stimulus and the magnitude of the electrical response of the nerve, and that the relation falls down for extremely high or low intensities (43). This seems to be presumptive evidence against the Fechner interpretation of Weber's law and the hypothesis of Heymans.

The work of Cobb and others serves to throw some doubt upon the generality of Heymans' law. Cobb and Ferree found that visual acuity and retinal sensitivity are greatest when the ratio of the brightness of the test field to that of the surroundings is about unity. The same holds true for the difference limen which is a minimum with this ratio, and serves

to emphasize anew the need of better control and definition of conditions in such investigations as those of Heymans and Spencer.

Burch and Allen did some work on sensory facilitation in which they found that visual stimulation of one eye had a reflex effect upon the other eye: for example, if the left eye is exposed to bright light for a time while the right eye is kept in darkness, the after-effect of this exposure of the left eye is to enhance the apparent brightness of the test object for the right eye (1, 4). Allen fatigued one eye with spectral light and found that there was an enhancement of brightness for the other eye (measured by the critical frequency of flicker) for the colors, red, green, and violet. Six colors (6600, 5700, 5800, 5050, 4800, and 4250 angstroms), which he calls equilibrium colors, produced no effect. Darkness adaptation of one eye, on the other hand, produced a diminution of brightness of the whole spectrum. Burch had formerly observed that if the left eye was exposed to white light, the scintillations in a spintharoscope seemed brighter to the right eye than if the left eye had been exposed to darkness.

Dunlap,[4] in observing the disappearance of a spot of light (1921).
seen peripherally against an otherwise dark field, found that vision of one eye can be inhibited by stimulation of the other eye. By using a shutter arrangement so that one eye at a time can be exposed to stimulation, he noted that if one eye (called the S-eye) is stimulated until the spot disappears, and then stimulation is shifted to the other eye (the D-eye), and then back to the S-eye, the spot is still invisible to the S-eye. There seem to be no time limits to this form of inhibition. If stimulation is shifted to the D-eye before the spot has disappeared, very often the spot fails to appear to the S-eye upon re-exposure. "If prolonged exposure of the S-eye is given, beyond the time of disappearance of the spot, and the stimulus is then shifted to the D-eye, it is found in many cases that the D-eye is also completely inhibited." Movement of the eye always re-instates the light-spot. These phenomena, Dunlap thinks, distinctly indicate "that some part of the central mechanism, connected with both eyes, is involved in the production of the effect."

[4] Dunlap, Knight, "Light-Spot Adaptation," *Am. Jour. Physiol.*, 55:201 (1921).

There is evidence of a similar type of inhibition and facilitation in certain forms of action, i.e., types which accompany voluntary adjustments but seem to be independent of voluntary control. Among these are the well-known dynamogenic effects of simultaneous stimuli, the first work done under the name *dynamogenesis* being that of Féré.[5] He found that various stimuli such as cutaneous, auditory, visual, gustatory, and olfactory, re-inforced the pressure a subject could exert on a dynamometer. Cleghorn[6] used the graphic record from an ergograph, and found that if a stimulus was given when the muscle just started to contract (voluntarily), the contraction was greater and the relaxation was quicker and more complete than when no stimulus was given. Hofbauer,[7] using the ergographic method, found that when a subject was contracting a group of muscles rhythmically to the sound of a metronome, a pistol report would increase one contraction, but the next contraction would be less than the average, thus causing first re-inforcement, then inhibition. Re-enforcement is greatest when the movement occurs immediately after the report, but continues in diminished amount up to .5 sec., then inhibition sets in and continues up to about 1.0 sec.

More germane to the present investigation are the various studies in facilitation and inhibition by the reaction-time method. Of special interest in the animal field is the work of Yerkes on the frog.[8] Using a 16 c.p. light as a reinforcing or inhibiting stimulus, he measured the time it took for the frog to respond to an electrical stimulus by jumping from a wire grill. Without the light there was a range in reaction-time of 152-329 milliseconds. If turned on one or two seconds before the electric stimulus, reactions were completely inhibited. If his fingers were moved past the window of the reaction-box about .1 sec. before the shock, the reaction-time was facilitated, but if moved continuously for 1 sec. it was inhibited. In another experiment he started a red disc vibrating .1 sec. before the electric stimulus was given, the average reaction-times for shock alone, and for the concurrent stimuli were respectively, 147 and 126; when the visual stimulus preceded by .5 sec., the average times were respectively 143 and 230.

[5] "Sensation et Mouvement," p. 26-50 (1887).
[6] Cleghorn, *Jour. Physiol.*, 1:336 (1898).
[7] Hofbauer, *Arch. f. d. ges. Physiol.*, 68:546 (1897).
[8] Yerkes, R. M., "The mutual relations of stimuli in the frog *rana clamata*," *Harvard Psych. Studies*, 2: 545-75 (1906).

More interesting is his study of audition in the frog by means of facilitation. It is difficult to condition the frog to react to sound alone. Sound seems to serve as a warning signal, hence, the frog seldom gives visible motor response to sound. The effect of sound was measured by the increase in amount of reaction to a tactual stimulus. The frog was strapped to a saddle and the movements of the hind foot were measured against an upright metric scale. A pendulum was used to control the time interval between the audition and tactual stimulus. The auditory stimulus was a bell or sound hammer, the tactual was a rubber cone which struck the frog just back of and between the ears. For momentary stimulation, zero re-enforcement occurred at .35 sec. Re-enforcement appears for intervals 0 sec., .15 sec., .25 sec., and inhibition at .45 sec. and .65 sec. At .9 sec. inhibition has disappeared. Prolonged auditory stimulation re-enforces from 0-1.2 sec.; inhibition then appears and continues up to 1.8 sec. Re-enforcement seems greater, and inhibition seems to appear sooner and last longer in females than males.

By means of this facilitating effect of sound upon the reactions of the frog, he was able to determine the range of hearing,—hearing in air and water, and hearing with the tympanum removed. As an example, he gives the following table for a female for the Galton whistle:[9]

Frequency	*Tactual reaction*	*Aud.—tactual*
5000	2.8 mm	4.65 mm
8000	2.6	5.45
10000	2.1	4.2
Puff of air	2.45	2.3

The result with the puff of air shows that the tone was the effective stimulus in the other series.

Todd measured the reactions of three subjects to the presentation of visual, auditory, and electrical stimuli (27). The stimuli consisted of a 2 c. p. lamp, a sound hammer, and electric shock; the onset of the stimuli and starting of the chronoscope were controlled by the motion of a large belt-driven wheel revolving at the rate of .8 of a revolution per second. Time intervals between the stimuli were controlled by placing the stimulus contacts at different positions on the wheel. The

[9] Yerkes, R. M., "The sense of hearing in frogs," *J. Comp. Neur.*, 15: 279-305 (1905).

stimuli were presented singly and simultaneously in doublets and triplets. In the case where the subjects were instructed to react to a specified stimulus of the combination he found that the reaction-time to a given stimulus was shortened by the simultaneous presentation of other stimuli. Later he measured the reactions for two subjects where they were instructed "to react to the group as a whole with no effort to attend to any of the elements," and concluded, since the reaction-times are about the same as when the subjects were instructed to react to a specified member, that the subjects were unable to single out and react to one member of a combination. It seems to the writer that the published data lend themselves more easily to the reverse conclusion; namely, that the subjects were reacting to a certain member of the combination in both cases, and that the other stimuli only operated to facilitate or re-enforce. At any rate, Todd had no objective check as to whether the subjects were actually reacting to the combination or to a single stimulus.

The following table gives the averages for Todd's three subjects for reactions to a specific stimulus of the combination, reactions always being made to the first stimulus designated in the combination,—e.g., L E is a reaction to light accompanied by shock:

Subject	*M*		*P*		*T*		*Gross*	
	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
Light	168.0	12.0	175.6	5.7	185.8	7.2	176.4	8.3
LE	145.9	10.1	140.4	9.6	157.4	7.9	147.9	9.2
LS	131.3	13.6	136.9	4.7	160.1	8.5	142.7	8.9
LES	114.4	4.8	123.8	4.8	133.8	9.1	124.0	6.2
Electric	141.5	13.6	135.1	8.6	152.1	9.6	142.9	10.6
EL	129.9	11.0	132.7	8.4	144.6	6.0	135.7	8.4
ES	123.7	13.5	122.0	7.5	136.8	7.8	127.5	8.4
ELS	124.6	14.5	125.0	4.9	138.1	11.2	129.2	10.2
Sound	134.9	9.3	131.9	5.7	160.5	7.3	142.4	7.4
SL	135.5	9.0	133.5	8.8	157.3	7.4	142.1	8.4
SE	125.5	7.4	122.8	4.9	153.0	8.6	142.1	6.9
SLE	121.7	14.8	123.6	7.0	142.5	6.3	129.2	9.3

Some reactions were also taken for two subjects for the successive combination of stimuli. The light always came last, and the subject was instructed to react to the light. The E and S preceded the light by evenly spaced intervals. Inhibition seemed to be greatest at the 180 milliseconds interval, be-

coming less for the longer and shorter intervals. The trend of the results is indicated in the following table:

Reaction-times to Successive Stimuli with Graded Intervals

Subject P				*Subject T*			
S-E-L		*E-L*		*S-E-L*		*E-L*	
Interval		360ms				360ms	
Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
180.5	5.3	182.8	3.3	222.6	12.3	217.5	8.1
		180ms				180ms	
203.1	18.3	222.3	6.9	213.8	18.9	218.4	5.7
		90ms				90ms	
173.9	7.7	173.6	7.4	180.0	8.3	175.3	9.0
		45ms				45ms	
159.9	7.8	156.6	11.2	177.1	7.6	182.4	9.0

That there is a tendency to give more attention to one stimulus than another is indicated by the work of Deuchler, and Dunlap and Wells (11, 13). Deuchler found some evidence that the reaction-time to three stimuli varied according to which "component was apperceived." Dunlap and Wells instructed their subjects to react to a specified stimulus of the combination, light and sound, and found that the reactions were shorter when they were made to the sound than when the attention was directed to the light. The results for the four subjects were as follows (S and F mean sound and flash, the capitals designate the stimulus reacted to):[10]

Stimulus	*S*	*F*	*Sf*	*Fs*
Sub J, Av.	107.1	155.7	107.0	113.8
M	97.8	157.6	94.3	120.4
W	119.5	175.3	123.3	144.2
D	106.0	166.6	112.2	119.5
Gen Av.	107.6	163.5	109.2	124.5

However, the reaction-times for light of the combination were shorter than for light alone, and they undertook a series of discriminative experiments to determine whether the subjects were actually reacting to the light, or perhaps unconsciously reacting to the sound. They found that the reaction-times to light and sound discriminated from sound were shorter than for light alone discriminated from sound, and this, they believed was evidence that the subjects in the previous experiments were reacting to the light (as instructed)

[10] Computed by Todd, "Reaction to Multiple Stimuli," *Arch. of Psych.*, Vol. XXI, No. 3, p. 42.

and not to the sound. It is the writer's opinion that this conclusion is not warranted by the data, and that the results of the two experiments are not comparable in this way because the mental "set" or adjustment is different for the simple reactions than for the reactions with discrimination.

Robert MacDougall[11] measured the reaction-times for two subjects to sound with varying intensities and qualities of visual stimulation. The times were shorter and more irregular in faint light than in bright light, an effect which he thinks is "due to factors of novelty and attention, rather than any direct dynamogenic relation between sensory and motor processes." Reactions to colored light were faster than under white light, in the ratio of 130.7 to 148.4. Likewise, reactions under colored light were shorter than those made in darkness, in the ratio of 130.7 to 140. Again the mean deviation is greater for colored than for neutral illumination. MacDougall concludes that the "factor determining the rate of response to homogeneous sensory stimuli appears not to be material differences in their quality or intensity, but the degree to which they succeed in stimulating the attention of the reactor, and thereby increasing the general nervous excitability of the moment."[12]

Johnson had his subjects react with discrimination to the disappearance of two spots projected upon a circular test field of foveal area, reactions being made with the right or left hand according to whether the right or left spot disappeared (21a). He found that the reaction-times varied with the brightness of the surrounding field,—the time, the relative variability, and the number of errors being least when the ratio of the surrounding field to the test field was about unity.

The work of G. R. Wells shows some evidence of inhibitory and facilitating factors in reactions to different temporal magnitudes of stimulation (28). In one part of the experiment, he had his subjects react to five durations of auditory stimulation ranging from 7 to 106 milliseconds. In another part of his monograph he describes an experiment in which the reactors reacted to five durations of light and five durations of darkness. Regarding the data for auditory stimuli Wells

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[11] Robert MacDougall, "On the influence of varying intensities and qualities of visual stimulation upon the rapidity of reactions to auditory stimuli," *Am. Jour. Physiol.*, 9: 116-121 (1903).

[12] Robert MacDougall, *op. cit.*, p. 121.

concludes that when intensity difference is not present "the durations of an auditory stimulus does not materially affect the time of reaction." If, however, we examine the data and calculate the probable errors for the differences between extreme values of duration, it seems that there is perhaps some evidence of consistent differences. All of the subjects reacted quicker to the 30 than to the 7 millisecond duration, the difference for three of the subjects being three to five times the probable error. There also seems to be a tendency for the subjects to react slower to the 106 interval than to the intermediate range of durations. D, the only practised subject, showed a difference between the 30 and 106 interval of 10 milliseconds which was nine times its probable error. These figures seem to indicate that perhaps there may be an optimum duration. The reactions to the light seem to indicate more clearly an optimal duration than in the case of the sound. This seems to differ for different subjects, ranging from 25 to 150 milliseconds for both light and darkness, but it seems that each individual's optimal duration is different for the presentation than for the removal of the stimulus. The facilitating factor that suggests itself here is that for any given duration of stimulation, the initial excitation was re-enforced at the cessation of the stimulus by excitation of the reverse order, and as long as the durations were as long or longer than the action-time of the retina and shorter than the normal reaction-time for the stimulus, the second excitation in the reverse direction might facilitate the reaction. There is the further possibility that the subjects tended to give closer attention to the shorter durations because of the greater difficulty of perceiving them; if the durations had been presented in irregular order, Wells would probably have had a fair check on whether the attentional factor was the significant one.

Since the present investigation deals with reactions to both the onset and removal of stimuli, it will be relevant at this point to discuss some of the studies on reactions to the cessation of stimuli. Woodrow (30) measured the reaction-times for the beginning and cessation of auditory and visual stimuli at different intensities. He made no quantitative evaluation of his stimuli, but merely designated them as "bright" and "weak" in the case of light, and as "medium, weak, and liminal" in the case of sound. Woodrow concludes from his data that "there is no appreciable difference between reaction-

time to the beginning of a stimulus and its cessation, no matter what the intensity of the stimulus and no matter what its mode," and sets up a hypothesis to account for the lack of disparity between the two forms of reaction; namely, that changes of reaction-time with increase or decrease of intensity are due primarily to an increase or decrease of attention.

Woodrow uses these results in an attempt to show that the conventional explanations of the dependence of reaction-time on intensity of stimulus by some kind of neural resistance are untenable (30). The most widely accepted theories of this kind are those of Piéron and Sherrington, the former asserting that the time is a function of the latent sensory period of the first receptive neurone, and the latter maintaining that it is dependent primarily upon resistance to transmission across the synapses. Both imply the concept of resistance to be overcome, so that the total effect of a stimulus must exceed a minimal amount before it will initiate a response. According to this conception, the weaker the stimulus the longer it must act to pass beyond the minimal limit. But Woodrow asserts that if it takes longer for the weak stimulus to overcome this resistance at the onset, we cannot also argue that the same thing would be true at the offset of the stimulus. "If we make a slight impression on the skin," he says, "it will disappear or fall below a prescribed threshold quicker than if it is deep. The after-image of a bright light lasts longer than that of a faint light. A string vibrating with large amplitude requires a longer time to come to rest, or to fall below any given threshold than one vibrating with small amplitude. The plasma membrane of a nerve cell would recover from a slight increase in permeability more quickly than from a great increase in permeability." If it takes longer for the photochemical process of the retina to get started for a weak stimulus than for a strong, it ought to take less time for the effect of a weak stimulus to fade away than that for a strong.

We might use an argument similar to Woodrow's when we are dealing with a summation of excitations, as in the case of reactions to the simultaneous presentation and removal of two or more stimuli. The investigations of Dunlap and Wells (13), and Todd (27) seem to indicate that the time of reaction to a given stimulus decreases when other stimuli are presented at the same time. Now, if we assume that the decrease in reaction-time to simultaneous stimuli is due to the

cumulative effect of additional impulses flowing into the central nervous system, we can argue that the same hypothesis would be inadequate as an explanation of a decrease in reaction-time to the removal of the same stimuli. If the cumulative effect of many stimuli is a greater influx of energy which tends to shorten the time of reaction, it would follow from a similar line of reasoning that reactions to the removal of simultaneous stimuli would be longer than reactions to the component stimuli, for it would take longer for the effect of a large amount of energy to fade away than it would for a small amount.

Proceeding on this hypothesis, the writer[13] measured the reaction-times for the simultaneous presentation and removal of auditory and visual stimuli, and also for the stimuli taken alone. The auditory stimulus was produced by a 75 ohm wireless receiver in circuit with the secondary of an induction coil, the primary of which was interrupted by a 100 d.v. electromagnetic tuning fork, and was not a part of the circuit operating the fork. A condenser was shunted around the mercury cup to minimize sparking at the break. The opening of the stimulus circuit was arranged so that both terminals of the secondary were cut off from the receiver at the same time, a procedure which was necessary on account of a low hum in the receiver when only one lead was broken.

The visual stimulus circuit consisted of an inch spark coil, a Geissler tube, and a set of electrolytic interrupters connected to the 220 volt alternating current mains of the University power plant. When in operation, the Geissler tube produced a low humming noise, to get rid of which, the tube was suspended in an evacuated glass container. This container was placed in a black box having an aperture covered with heavily ground glass.

The reactor was seated in a dark room with his eyes about three feet from the aperture of the box, and with his left ear comfortably placed within the circumference of a cloth-wrapped ring. With this arrangement the ear was about six inches from the diaphragm of the receiver. The preparatory signal for the presentation of stimuli was the click of a telegraph sounder, and for the removal of stimuli the signal was their presentation. The control apparatus, including a Hipp

[13] Masters Thesis, Univ. Nebraska, "Cessation reactions to light and sound," (1916).

chronoscope and the apparatus for the production of the stimuli, were situated in another room. Only one intensity (unmeasured) was used for each mode of stimulation.

The results obtained seemed to indicate that some individuals could react more quickly to the presentation of a stimulus, that a few could react faster to the removal, and that the times of others were about the same for the two forms of reaction, but, more individuals could react more quickly to the beginning than to the cessation of stimuli. Of eight practised subjects, the differences between cessation and beginning reactions for four of the reactors were less than three standard deviations (S.D.'s) of the difference, the reaction-times for three subjects were less for the beginning reactions by a difference of more than three S.D.'s of the difference, and one subject reacted more quickly to the removal of the stimulus by a difference equal to 4.2 S.D.'s of the difference. Similar relations hold for the reactions to visual stimuli, three of the subjects (the same three for the auditory) reacting more quickly to the presentation, and one reacting more quickly to the removal of the visual stimulus. These results seem to furnish presumptive evidence against Woodrow's conclusion that there is no appreciable difference between reaction-times to the beginning and cessation of stimuli, but on the contrary that individuals probably vary in this respect.

A careful examination of Woodrow's results seem to indicate that his conclusions are not warranted by the data. In six of the cases the differences are more than four times their probable error, three giving shorter beginning times and three giving shorter cessation times. The direction of these differences, however, are not the same for the same observers for the different modes. A summary of his results is given in the following tables:

Sound

Mode	*Intensity*	*Subj.*	*Beginning Reactions* Av.	Av. M.V.	*Cessation Reactions* Av.	Av. M.V.
Sound	Medium	Ht	119	16	121	15
"	"	Vs	137	17	143	17
"	"	Sz	148	19	148	21
"	Weak	Ht	184	26	183	33
"	"	Vs	174	20	167	22
"	"	Sz	209	33	218	33
"	Liminal	Ht	779	130	745	133
"	"	Vs	875	226	882	168

Light

Mode	*Intensity*	*Subj.*	*Beginning* Av.	*Reactions* Av. M.V.	*Cessation* Av.	*Reactions* Av. M.V.
Light	Bright	Ww	154	16	151	16
"	"	Ht	162	21	167	18
"	"	St	183	21	184	19
"	"	Vs	192	19	185	17
"	"	Sz	201	22	201	22
"	Weak	Ht	205	33	203	24
"	"	Vs	243	26	234	21
"	"	Sz	268	28	250	26

That there are consistent individual differences in reaction-time for the presentation and removal of stimuli, is indicated in the work of G. R. Wells (28) who had six subjects react to five durations of light and five durations of darkness. One subject showed a consistent difference in favor of the presentation and another in favor of the removal of the visual stimulus. A tendency in a given direction was not so definitely shown by the other four.

Recently, Holmes measured the reactions of two subjects to the presentation and removal of three intensities of visual stimulation (33), and concluded that the arithmetical increase of reaction-time with geometrical decrease of intensity is less for cessation than for beginning reactions, and "that cessation reactions are quicker, this difference becoming greater as the intensity decreases." The statistical reliability of Holmes' results is higher than those of Woodrow and most of the data is consistent except possibly subject J, who for one set of reactions gave differences between onset and cessation of about 8, 16, and 23, respectively, for three intensities; six months later he got approximately the *same* difference (about 12 ms) for each intensity.

The apparent disparateness of the results of the workers mentioned is probably due in part to differences in operating conditions. It serves to emphasize the need of limiting and more accurately defining the conditions under which such investigations are carried out. Woodrow defines his intensities by such terms as "liminal," "weak," and "medium," which probably mean something different to everyone who reads them, and consequently make it impossible to reproduce the conditions of the original experiment. Another point to be taken into consideration is the nature of the immediate surroundings. That such conditions should be carefully defined

seems to find ample support in recent findings, e.g., visual acuity is greater and the difference limen is less for a field in similarly lighted surroundings than when the field is surrounded by darkness (5, 6, 7, 15). In making comparative studies of reactions to the presentation and removal of stimuli it is also probably very essential to make empirical determinations of the most obvious sources of constant error, because in changing over from one form of reaction to the other the constant error may change both in magnitude and direction. Among such sources are lack of synchronism of the timing and stimulus circuit operations, different damping constants at make and break, and if a circuit contains inductance, capacity, and resistance, transient currents will behave differently according as the impedance is complex or real.

Granting Woodrow's conclusion that there is no difference in reaction-time to the beginning or cessation of a stimulus, it seems doubtful whether he is warranted in the sweeping generalization he makes in regard to the theories of Piéron and Sherrington. If we look at the matter in a different way, and assume that it takes a certain minimal amount of work to overcome the inertia of the sense-organ, this would be accomplished the quicker by the stronger stimulus because more work would be done per unit time; and when the stimulus is removed it would be quite natural to expect the initial decrement per unit time in the return of the receptor from its state of excitation to equilibrium to be greater when the excitation is large. This perhaps can be made clearer by returning to Woodrow's analogy of the vibrating string. The damping resistance of the air varies directly as the velocity of the moving string, so that its amplitude falls off exponentially with the time. The decrement therefore is larger, the greater the amplitude, so that more energy is used up per unit time when the amplitude is large than when it is small. Carrying our analogical reasoning a step further, we might compare a sense-organ to an elastic string—the further it is stretched the faster it does work in returning to its state of rest, so that a given quantity of work will be done in less time if the stretch is large than if it is small.

Furthermore, the experimental evidence we have at the present time seems to indicate that sensory intensity is not a function simply of quantity of work done, but of the rate at which the work is done; that rate of change is the *sine qua*

non of sensation (33). If pressure is applied gradually to an excised nerve it may be crushed without eliciting a muscular response, and the temperature of water may be gradually raised to the boiling point on a frog without apparently stimulating it (34). The same seems to hold true for dermal sensitivity where the rate of change is subliminal (36).

The writer's measurement of reaction-time to the presentation and removal of simultaneous stimuli seems, as in the case of reactions to the individual components, to indicate individual differences. In this experiment the reactors were instructed to react to the "combination, light and sound." Reactions to light and sound alone were also given at the same sitting, the order of giving the different modes being changed at each sitting to neutralize the effects of position in the series. Among eight practised subjects, four reacted quicker to the onset by a difference more than four times the S.D., one reacted more slowly to the onset by a difference of 4.4 S.D., and the others gave differences from .2 to 3 S.D. On the other hand, all the subjects reacted more quickly to the sound than to the combination, light and sound, except one, and his time was faster for the combination at the onset and the same for the cessation. The reason for this difference is not clear, but his introspections seemed to indicate that he was unable to resist giving most of his attention to the sound. In general, the introspective data seemed to indicate that the more evenly the attention was divided between the two modes, the greater the increase of reaction-time to light and sound over that for sound alone. This seems to indicate the importance of the adjustmental factor that has been stressed so strongly by a few modern workers, and suggests a means of measuring attention by reaction-time (20, 29, 30, 31, 32).

Up to this point, we have been dealing with reactions to disparate stimuli. What happens when the stimuli are the same, or when the same type of sense-organs are activated by the same stimulus? Bliss[14] found that reaction-times to a given sound are shorter when heard by two ears than when heard by one. That there are possibly central facilitating and inhibitory factors involved in the case of visual stimulation is strongly indicated by some work of Poffenberger on reactions to monocular and binocular stimulation (23). Using three

[14] Bliss, C. B., "Investigations in reaction-times and attention," *Yale Stud.*, 1: 1 (1892-6).

subjects, he measured the reaction-times to light for each eye and for both eyes using a light stimulus of foveal area. A summary of the results follows:

	One eye			Both eyes			
Subject	*No. rts.*	*Av.*	*M.V.*	*No. rts.*	*Av.*	*M.V.*	*Diff.*
T.....	800	201.3	8.6	200	184.6	5.0	16.7
P.....	800	174.8	6.0	400	160.4	5.0	14.4
A.....	400	191.2	11.0	200	178.1	6.0	13.1

On the average, there was a reliable difference of about 15 milliseconds between reactions to monocular and binocular stimulation. This cannot be explained, as Poffenberger observes, by an increase in brightness in the case of binocular stimulation; the apparent difference in brightness value for one eye compared with that for two eyes offers insufficient grounds for the large difference in reaction-time. These results seem to suggest that doubling the area of stimulation by stimulating both eyes does not appreciably re-enforce the total sensory effect, but that it does offer a comparatively large re-enforcement of the motor effect.

SECTION III

Apparatus and Method

1. *Essential Conditions and Sources of Error*

As stated on another page, the present study is an attempt to determine the influence of the presentation and removal of sound upon reactions to the appearance and disappearance of light. To do this successfully requires a technique that will adequately take account of certain important conditions and sources of error.

(a) As noted in the last section, previous investigators failed to devise any adequate check on what the subject was reacting to. There should be an objective check, other than the verbal report of the subject, as to whether the reactor is following instructions, and reacting to a designated stimulus of a constellation of disparate stimuli. Likewise, if instructed to react to the "combination of stimuli," we need some objective means of determining whether the reagent is reacting to the "aggregation," or to one of the components. Is a divided attention more effective in producing a rapid response, than concentrated attention upon one stimulus in a situation in which the other stimuli act merely as facilitators? A reactor may be extremely conscientious and still be unable to react to a given stimulus to the exclusion of others. If light and sound always come together, he may find great difficulty in "setting" himself to react merely to the light, in fact, judging from what we know about the conditioned reaction, a subject may unconsciously "set" himself to react to the sound. In any case, it would not be safe to take the verbal report of the subject as a measure of his ability to follow instructions. One way to get objective control of the situation is to present the additional stimuli in irregular order, so that the reactor never knows when the added stimuli appear.

(b) It may require more or less attention to react to one combination than to another. For example, it may be more difficult for the reactor to attend to the presentation of light than to its removal, or a light-sound stimulus may be easier to attend to than light alone. For convenience and the want of a better name, we will call the cause of such differences the *volitional factor*. In order to give greater comparability to

the results for the effect of the presentation and removal of sound upon reaction-times to light, the volitional factor ought to be controlled so that its effects on the average would be the same for the different modes of stimulation. One way to do this is to prevent the subject from knowing when the sound is going to be presented or removed. If the reactor knows what is coming, it gives him a chance to prepare or "set" himself (consciously or unconsciously) to react to light or darkness accompanied by a known stimulus.

(c) Reaction-times to the beginning and cessation of stimuli, to be comparable, should occur as nearly as possible in the same stimulus situations. Woodrow, in his work, used a preparatory sound signal for beginning reactions but used no preparatory signal for the removal of the stimuli except the onset of the stimuli themselves. A special auditory signal may possibly act as a facilitator and if given for one mode and not for another, the reaction-times cannot be directly compared because of differences in antecedent conditions, or a sound signal may act as a detractor for one mode, and as a facilitator for another. For such reasons, no preparatory signal was used in the present investigation at all, the manner of presenting and removing the stimuli being such that the need of a signal was unnecessary.

(d) Another possible source of error is the effect upon reaction-time of varying degrees of light or dark adaptation. To equalize the effects as far as possible, the interval of light or darkness preceding reaction should be about the same throughout the series, or at any rate, the interval in each case should be known.

(e) Taking reaction-times to different modes of stimulation, such as to light and darkness usually means a change of some kind in the mechanical procedure for giving the stimulus. Consequently, it is very essential to eliminate constant errors as far as possible, and to make empirical determinations of the most obvious sources of constant error, because in changing over from one form of reaction to another, the constant error may change not only in magnitude but direction.

(f) The essential conditions of the experiment should be defined in terms that will enable other investigators to repeat the experiment, chief among which are the form, the frequency characteristics, and the energic values of the stimuli,

and the elimination of irrelevant, rhythmic, or variable distracting stimuli from the general stimulus situation.

2. *Method*

In order to meet the first four conditions enumerated above, the following procedure was adopted: the subject reacted to a visual stimulus which appeared and disappeared rhythmically in intervals of either 3.5 or 4 sec. A special preparatory signal was unnecessary, because the removal or presentation of the light which just preceded the one which the subject next reacted to served the purpose of a preparatory signal. To prevent the reactor from anticipating and successfully reacting by estimating when the next stimulus change occurred, the intervals of 3.5 and 4 seconds between appearance and disappearance of the light occurred in irregular order in the form of a chance distribution. These intervals were accurately timed and automatically controlled by machinery so that the position of each length of interval in the series and the number of intervals of each length could be checked off after the experiment was over.

The appearance and disappearance of the visual stimulus was accompanied by a simultaneous but *irregular* presentation and removal of the auditory stimulus. The presentation and removal of the sound occurred as a chance distribution and was also controlled automatically by machinery so that the positions of the different modes in the series could be sorted out after the experiment was over. The irregular presentation and removal of the auditory stimulus was intended to compel the subject to follow instructions by reacting to the light instead of the sound. In other words, by denying the reactor foreknowledge of when the presentation or removal of the sound was to occur, it was hoped to prevent any pre-adjustment on the part of the subject for the reception of and reaction to the auditory stimulus.

This procedure gives eight different modes of stimulation, as follows: (1) light and sound, (2) darkness and quiet, (3) light and quiet, (4) darkness and sound, (5) light with the tonal stimulus continuing without change, (6) light with a continuance of quiet, (7) darkness with the tonal stimulus continuing without change, (8) darkness with a continuance of quiet. Some notion of the sequence of stimulus combinations can be secured by a symbolic representation of a short

series of them. In the series below, L stands for light, Q for quiet, S for sound, and D for darkness:

L D L D L D L D L D L D L D L D L D L D L D
S S Q Q S Q S S S Q S S Q Q Q S Q Q S S Q S Q Q

To insure constancy of lighting conditions, reactions were not made in daylight, but in a room used especially for dark room work. In fact, the reactor's room was dark throughout the experiment. The only light and dark adaptation then was that which occured between reactions, during the presence or absence of the visual stimulus. Since the intervals between reactions were the same and of known length we have some measure of light and dark adaptation in terms of the length of the interval.

To prevent the subject from being conditioned by noises of various kinds, noise-making machinery as well as the operator were located in another room. This includes the chronoscope and mechanism for the control of the order and rate of presentation and removal of the stimuli. Elimination of the disturbing influence of experimenter and noisy machinery gave a general stimulus situation that was as nearly constant as it was possible for us to make it, and makes it possible to duplicate the essential conditions of the experimental setting.

A further guarantee of reproducibility of the essential conditions of the experiment was to make it possible to give a *quantitative* statement of the nature of the light and sound; namely, the energic and frequency characteristics of the stimuli. For the auditory stimulus a pure tone of known frequency and intensity was used. Intensity was calculated for work done on the tympanum per unit area. Light of known wave length was thrown on a round, ground-glass window located at such a distance from the observer that it subtended an angle of three degrees at the reactor's eye. An ophthalmometer head rest was used to keep the distance constant between the window and the reactor's eyes. The intensity of the light was measured at the position of the reactor's eyes in microwatts per square millimeter with a radiometric apparatus consisting of a Coblentz vacuum thermopile and Thompson iron-clad galvanometer, and a radiation standard furnished by the Radiometric Division of the Bureau of Standards.

3. *Apparatus*

The apparatus can be conveniently described under the following subheads: (a) Apparatus for the production of sound, (b) apparatus and accessories for the production and measurement of chromatic light, (c) the exposure mechanism, (d) mechanism for control of the time and order of presentation and removal of the stimuli, (e) the timing apparatus including the chronoscope and accessories.

The apparatus for the production of sound was designed to produce pure tones of constant frequency and intensity. This involves the use of a generator giving alternating current of pure wave form for operating the vibrating system and a satisfactory transformation of the impressed electrical energy into sound vibrations free from harmonics. The electrical energy is supplied by the oscillator outlined in Fig. 1. It is an ordinary Hartley circuit with L_1, L_2, as inductance consisting of three wooden core coils with a combined inductance of 20 henries. C is a variable mica condenser, and V is the vacuum tube which acts as though it were a generator, and for convenience may be considered as such. The potential e_g impressed upon the grid is the drop across L_2, viz:

$$R_2 i_2 + L_2 \frac{di_2}{dt} - M \frac{di_1}{dt}$$

The potential E impresed on the plate circuit is a function of the amplifying constant and the pressure on the grid:

$$-\mu e_g = -\mu \left(R_2 i_2 + L_2 \frac{di_2}{dt} - M \frac{di_1}{dt} \right)$$

The rise in pressure in the plate circuit sets up oscillations in the oscillating circuit having a frequency depending upon the total inductance and capacity in the circuit. Since the resistance in the oscillating circuit is small, the frequency is approximately,

$$\frac{1}{2\pi} \sqrt{\frac{1}{LC}}$$

where L and C are the total inductance and capacity in the circuit.[15, 16]

[15] Cf. Van de Bijl, "The Thermionic Vacuum Tube," p. 174 ff.; L. A. Hazeltine, *R. I. E.*, 6:63 (1918); and R. A. Heising, *Phys. Rev.*, 17:365.

[16] The nature and limitations of the oscillator and some of the factors that must be taken into account in its design, become evident when we write down and solve the Kirchoff voltage equations for the a. c. com-

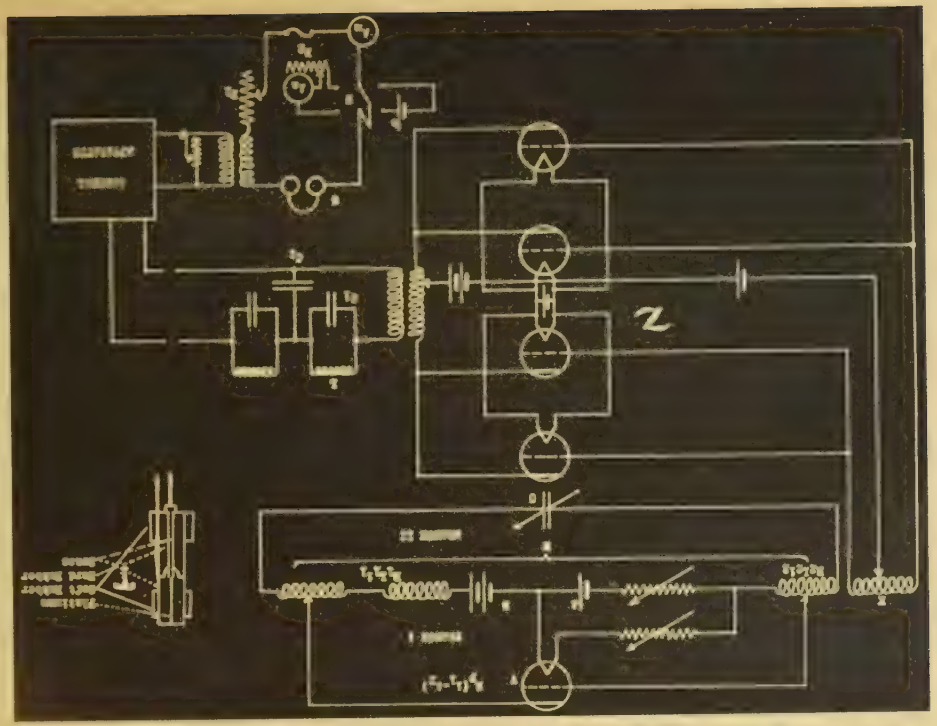

Figure 1. Oscillator and accessory apparatus for the production of sound. Oscillating current is generated in circuit containing vacuum tube V. L_1 and L_2, wood core inductances with a combined maximum inductance of 20 henries. C, variable mica condenser. K, small coil to take off a small amount of power to be amplified through the push-pull circuit Z. L, C_1, C_2, inductance and capacities of one unit of a low pass electric filter. G, thermophonic receivers worn on subjects' head. T, sectional layout of a thermophonic receiver. b, battery for sending direct current through the thermophone A_1, A_2 ammeters for measuring, respectively, the direct and alternating currents flowing through the thermophone.

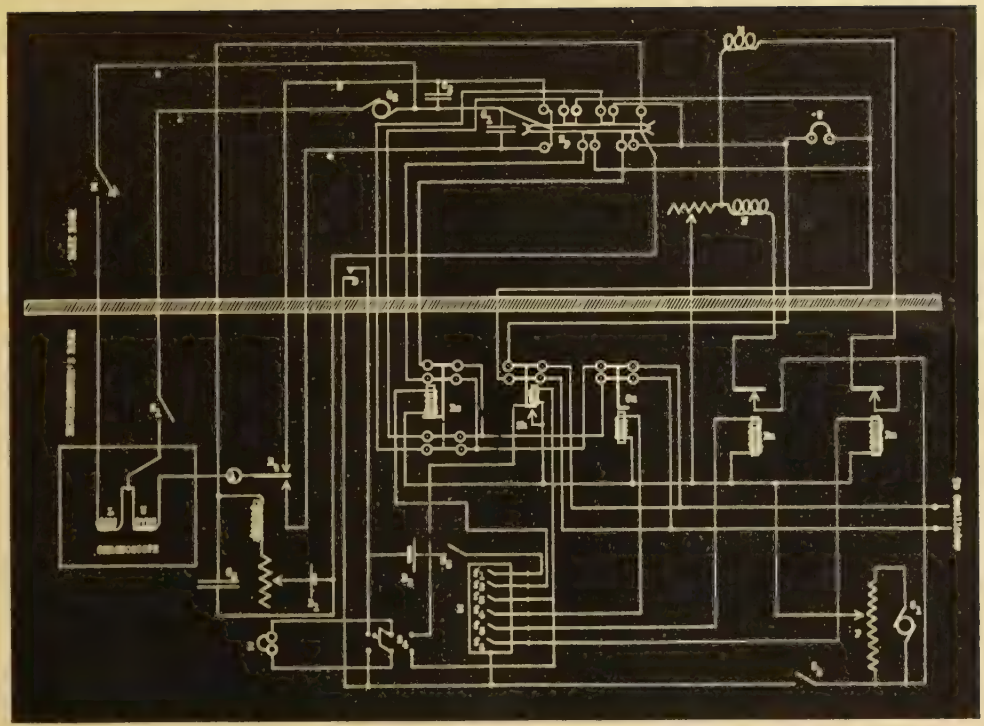

Figure 2.—Wiring diagram for timing, control and exposure mechanisms. The oblique lined space represents the wall between operator's and reactor's rooms. S_P, rocking mercury switch operated by pendulum shown in Fig. 4. C_1, C_2, C_3, condensers to minimize sparking. K, reactor's key. M and N, solenoids for holding pendulum in position. D, telegraph sounder, T, thermophonic receiver. E, electrode of stimulus control through contacts f_2—f_{10}, the relays R_{10}, R_{20}, for release of pendulum, and Re Sh, and Cu for control of the order of presentation and removal of the sound are operated. f_1 operates the sounder to warn the subject of the beginning of a series. R, receiver worn by experimenter for receiving signals for checking, beginning, and order of the series. R_1, relay operated in conjunction with chronoscope.

Footnote 16—continued

ponent of the two branches of the oscillation-plate circuit. For branch II we have (*cf.* Fig. 1),

$$R_p(i_1 + i_2) + \int \frac{i_2 dt}{C} + \frac{L_2 di_2}{dt} + R_2 i_2 - M\frac{di_1}{dt} = -\mu\left(L_2\frac{di_2}{dt} + R_2 i_2 - M\frac{di_1}{dt}\right)$$

For branch I,

$$R_p\ (i_1 + i_2) + L_1\frac{di_1}{dt} + Ri_1 - M\frac{di_2}{dt} = -\mu\left(L_2\frac{di_2}{dt} + R_2 i_2 - M\frac{di_1}{dt}\right)$$

By making a substitution of the form e^{xt} and solving the simultaneous equations obtained, we get an equation in x with real coefficients of the form,

$$x^3 + Ax^2 + Bx + C = 0$$

where,

$$A = \frac{R_p\ (L_2 + L_1 + 2M) + (\mu + 1)\ (R_2L_1 + R_1L_2)}{(L_2L_1 - M^2)\ (\mu + 1)}$$

$$B = \frac{R_p\ (R_1 + R_2) + (\mu + 1)\ (R_2R_1 - \frac{M}{C}) + \frac{M + L_2}{C}}{(L_2L_1 - M^2)\ (\mu + 1)}$$

$$C = \frac{R_p + R_1}{(L_2L_1 - M^2)\ (\mu + 1)\ C}$$

If we let P_1, P_2, P_3 be the roots of the equation, we have

$A = -(P_1 + P_2 + P_3)$
$B = P_1P_2 + P_2P_3 + P_3P_1$
$C = -P_1P_2P_3$

and since we expect the motion to be freely oscillatory (the resistance s of L_1 and L_2 is small, so no other condition is possible), x is complex, so that in order to satisfy the condition that the coefficients be real the roots must be of the form,

$P_1 = a + j\omega$
$P_2 = a - j\omega$
$P_3 = b$

Substituting in the equations for A, B, and C, and solving for a, b, and ω we have,

$a = 1/2A\ (C/A - B)$
$\omega^2 = C/A$
$b = -A$

The frequency can be calculated from the angular velocity C/A. The damping constant (a) of the oscillation circuit furnishes the condition for oscillation, according as (a) is negative or positive. If (a) is negative, the effective resistance is positive, and any oscillations that are started fall off exponentially to zero. But if (a) is zero or positive, the effective resistance is zero or negative, and the circuit will continue to oscillate indefinitely. 1/2A is always positive, so that continued oscillation depends upon the factor (C/A — B) being zero or positive. Since the resistance of the oscillation circuit is small compared to the plate resistance, it will be a sufficiently close approximation to assume $\omega^2 = 1/LC$, and drop the product R_1R_2C. We finally have then for the condition for oscillation,

$$\mu = R_p\ (R_1 + R_2)\frac{CL}{L_1L_2} + \frac{L_2}{L_2}$$

The above equation enables us to compute for a given amplifying constant and plate resistance what the constants for the oscillation circuit must be to cover a given range of frequencies; also, by differentiating $(R_1 + R_2)$ with respect to L_2 and equating to zero the best coupling can be determined for securing maximum reliability.

In order to prevent appreciable changes in the frequency due to small changes in inductance which would occur when the auditory stimulus circuit is opened and closed as when taking reaction-times, the receiver is not connected up directly with the oscillation circuit, but instead, a small amount of power is taken off by loose coupling at K, and amplified by the push-pull circuit Z. Finally, the energy passes through the low pass electric filters indicated in the diagram (Fig. 1). The filters were designed to cut out all frequencies above 1500.

The apparatus for transforming the electrical energy into mechanical energy was a problem of some difficulty because of the importance of terminal conditions in reaction-time work. As long as we are only interested in the steady state, the transient effects that occur at make and break are of little importance, because they will soon be damped out by the resistance of the air, leaving only the impressed vibration, which will be a pure sinusoid provided the impressed force is of pure wave form. But when terminal conditions become of importance as they do in reaction-time, it becomes desirable to minimize the importance of the transient phenomena occurring at the beginning and end of the disturbance.[17]

It was finally decided that a thermophonic receiver would best meet the conditions of the present investigation, because it contains no vibrating elements. A sectional view is shown of a thermophonic capsule at T, Fig. 1. A piece of hard rub-

[17] If we assume as a sufficiently close approximation that any element of the vibratory system is moving in accordance with Hook's law, and that the resistance to its motion is proportional to its velocity, we have for free vibration,

$$M\frac{d^2x}{dt^2} + R\frac{bx}{dt} + Kx = 0$$

where M is the mass, R is the resistance for unit velocity, K is the force of restitution for unit displacement, and x is the displacement. If we put $b = R/M$ (the deceleration for unit velocity due to R), put $\omega^2 = K/M$ (the acceleration for unit displacement), and equate to an impresse force equal to $F\cos\bar{\omega}t$, we have,

$$\ddot{x} + b\dot{x} + \omega^2 x = p\cos\bar{\omega}t \qquad (1)$$

where $p = F/M$ (the maximum acceleration due to the impressed force). The solution of the left hand member is,

$$Ae^{at} + Be^{-at} \qquad (2)$$

where $$a = \frac{-b \pm \sqrt{b^2 - 4\omega^2}}{2} \qquad (3)$$

ber is threaded and screws into a brass shell. A brass screw passes through the rubber as one terminal of the receiver, the other terminal is soldered to the brass shell. The thermal element consists of platinum wire .0018 cm. in diameter. A small capillary glass tube passes through the rubber to the sound chamber to allow slow leakage of the air to keep the sound chamber at atmospheric pressure. This capsule when used is inserted into the meatus of the ear.

The intensity and frequency of the sound is a function of the heating effect on the platinum wire. With pure alternating current the heating effect is

$$RI^2 \sin^2 \tilde{\omega}t = \frac{RI^2}{2} \quad (1 - \cos 2\,\tilde{\omega}t)$$

so that the frequency of the sound is twice that of the current. The acoustic wave can be made to follow the current wave by superimposing the alternating current upon a direct current

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Footnote 17—continued

A special solution involving $p\cos\tilde{\omega}t$ can be found most easily by substituting $e^{j\tilde{\omega}t}$ for $\cos\tilde{\omega}t$, solving and then taking the real part of $e^{j\tilde{\omega}t}$ as the special solution. Let $x' = Ae^{j\tilde{\omega}t}$ be a solution, then,

$$A = \frac{p}{j^2\tilde{\omega}^2 + j\tilde{\omega}b + \omega^2}$$

$$x' = \frac{p}{j^2\tilde{\omega}^2 + j\tilde{\omega}b + \omega^2} e^{j\tilde{\omega}t}$$

$$= \frac{pe^{j\tilde{\omega}t}}{\sqrt{(\omega^2 - \tilde{\omega}^2)^2 + \tilde{\omega}^2b^2}\; e^{j\tan^{-1}\frac{\tilde{\omega}b}{\omega^2 - \tilde{\omega}^2}}}$$

Taking the real part of x' we have for the special solution,

$$x = \frac{p\cos\left(\tilde{\omega}t - \tan^{-1}\frac{\tilde{\omega}b}{\omega^2 - \tilde{\omega}^2}\right)}{\sqrt{(\omega^2 - \tilde{\omega}^2) + \tilde{\omega}^2b^2}}$$

Adding (2) to this we get for the complete solution,

$$x = Ae^{\alpha t} + Be^{-\alpha t} + \frac{p\cos\left(\tilde{\omega}t - \tan^{-1}\frac{\tilde{\omega}b}{\omega^2 - \tilde{\omega}^2}\right)}{\sqrt{(\omega^2 - \tilde{\omega}^2)^2 + \tilde{\omega}^2b}}$$

When (a) is complex, (2) may be reduced to the form,

$$x = Ae^{-bt/2}\cos(Wt + \epsilon) \text{ where } W = \sqrt{\omega^2 - \frac{b^2}{4}}$$

the natural vibration of the system superimposed upon the forced component (4), which gradually fades away due to the damping factor $e^{-bt/2}$,

I_1 which is several times as large as the alternating component:[18]

$$R(I_1 + I \sin \bar{\omega}t)^2 = R\left(I_1^2 + \frac{I^2}{2}\right) + 2\,RI_1 I \sin \bar{\omega}t - \frac{RI^2}{2} \cos 2\,\bar{\omega}t$$

By making I_1 large compared to I, the double frequency term above can be made negligible.

Knowing the current values, I in the case of pure alternating current, I_1 and I in the case of the direct and alternating current, the dimensions, the specific heat of the thermal element and the diffusitivity of the medium, the pressure changes upon the boundaries (the tympanum of the ear may be one boundary) may be calculated.[19]

The light stimulus is produced within a given wave-length range by a special piece of dispersion apparatus, (A, Fig. 4), consisting of a constant deviation prism on a rotatable table, a collimating and telescope lens, and analyzing slit. The tubes were made large in diameter to take a series of black diaphragms to absorb stray light, due to reflection. The monochromatic light thus obtained passes through a lens shown at D, Fig. 4, which focuses the rays so that a hairline of light appears on the vane (c) of the pendulum. A vertical line of light gives a sharp cut-off and onset of the light when the pendulum passes through its vertical position. The light finally falls upon a screen H containing a circular, ground-glass window subtending an angle of three degrees at the subject's eye. The intensity of the light is measured with a

[18] H. P. Arnold and I. B. Crandall, "The thermophone as a precision source of sound," *Phys. Rev.*, 2 Ser., 10:22.

[19] Arnold and Crandall (*op. cit.*, p. 33) deduce the following equation for the pressure changes in a closed space for direct and alternating current:

$$A = \frac{.086\ RI_1IP\ \sqrt{K_o \sqrt{\Theta_1/273}}}{\gamma V_o \Theta f^{3/2}}$$

where P is the total pressure, K_o is the diffusivity of the gas at 0° C., Θ_1 is the absolute temperature of the gas near the thermal element, Θ_2 is the mean temperature of the gas, γ is the thickness multiplied by the specific heat per unit volume, V_o is the volume of the enclosed space, f is the frequency, and R is the resistance of the element.

Wente (*Phys. Rev.*, 2 ser. 10:52) notes that the formulae of Arnold and Crandall give results which are slightly in error. Later Wente (*Phys. Rev.*, 2 Ser. 19:333) using the fundamental differential equation for the conduction of heat in a gas, developed formulae for cases where the thermal element is metal foil, and also where the element is cylindrical (a wire), that give a closer approximation than those of Arnold and Crandall.

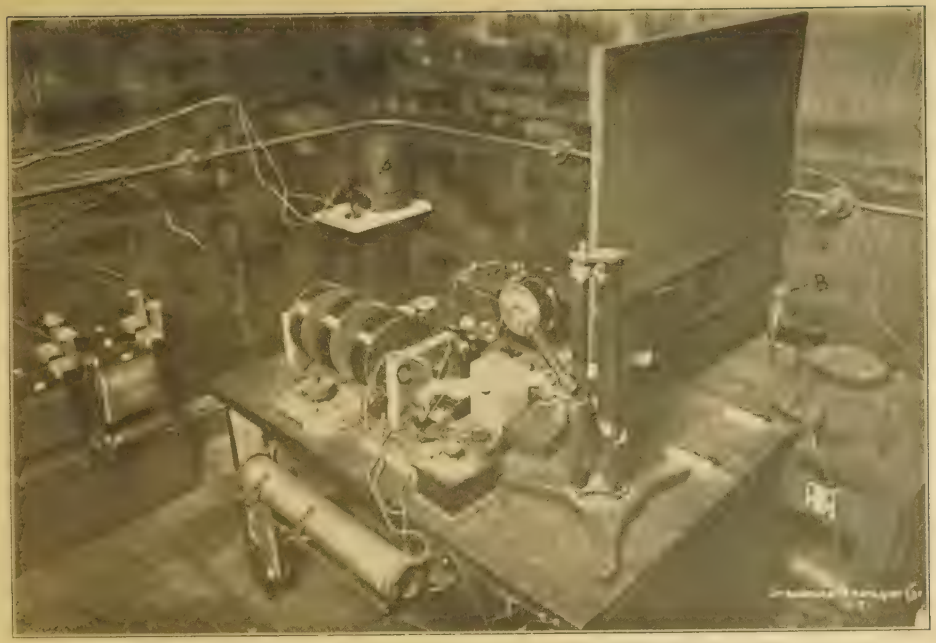

Figure 3. (A) vacuum thermopile and Thompson iron-clad galvanometer. The radiometric apparatus is calibrated against a radiation standard (B) furnished by the Bureau of Standards. (C) Oscillator with wooden core inductances to minimize the distortion—frequency range 8—50000. (D) Electric filters.

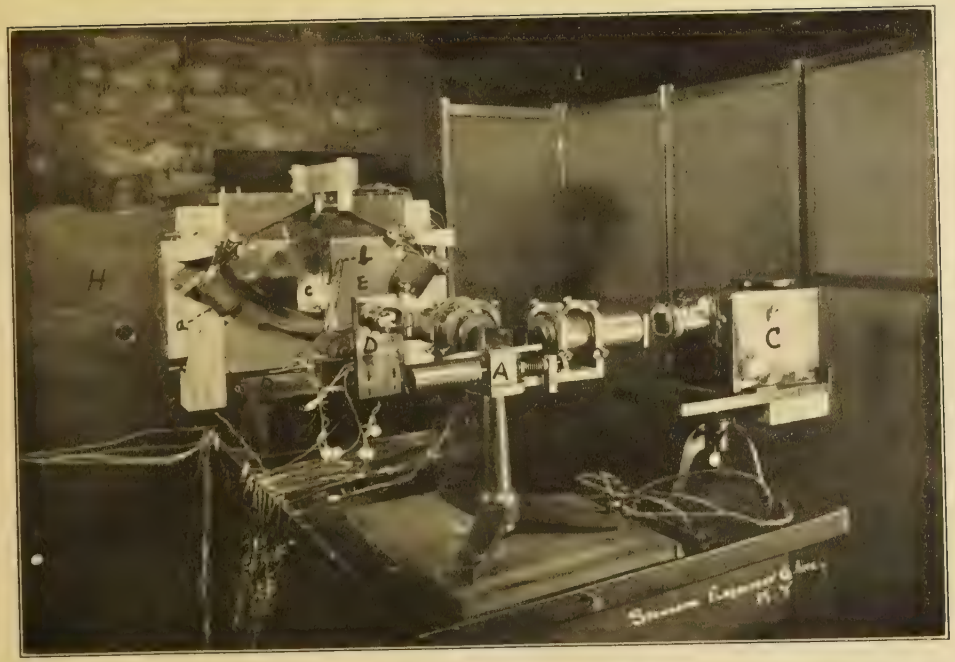

Figure 4.—(A), Monochromatic illuminator—constant deviation prism and wave-length drum—40mm. objectives—collimator and analyzer tubes of large diameter containing a series of diaphragms to absorb stray light. (B), Exposure apparatus for the presentation and removal of stimuli, and control of the timing mechanism of the chronoscope. (a), solenoids for catching and holding pendulum in position. (b), rocker arm and switch for sound and timing circuits. (C), Light source.

vacuum thermopile and sensitive galvanometer (A, Fig. 3). The thermopile is enclosed in a vacuum to prevent variations due to air convection currents. The radiometric apparatus is calibrated against a radiation standard (Bureau of Standards) whose radiation values are based upon absolute measurements and indirect measurements using the Stefan constant of total radiation of a black body. With this arrangement, after making a correction for absorption and reflection of the glass window of the thermopile, the radiation flux at the observer's eye can be determined in microwatts per sq. mm. from the galvanometric readings.

The reason for using radiometric apparatus and determining the radiation flux in absolute units instead of candles, is because it was believed that photometric determinations are too unreliable. The sensitivity curves of different individuals vary; in some, the maxima are sharp, while in others, the maxima are relatively flat. Ives, using the flicker photometer, found this variability between different observers to be the least in the middle region of the spectrum at about 5800A., the disagreements being 12 to 15 times as great at the violet and red ends of the spectrum. There is also the well known fact that photometric determinations vary with intensity of light and the state of adaptation and fatigue of the eye. Another point worthy of note is the observations of Burch and Allen that apparent brightness for one eye may be influenced by the state of color adaptation and fatigue of the other eye. Finally, photometric determinations always depend on a difference limen, and this varies for different observers and increases with increases of intensity. There is also the further observation of Cobb, that the difference limen varies according to the brightness of the surroundings.

The pendulum B, in its swing presents and removes the auditory and visual stimuli and starts the chronoscope located in the experimenter's room (Fig. 5). The rocker switch is operated by means of a rubber stud attached to the pendulum, which works in a slot in the rocker arm (b). In this way, the rocker switch executes a simple harmonic motion with the swing of the pendulum, the maximum velocity being at the point where the pendulum passes through its vertical position. This insures a rapid make and break of the mercury contacts, thus cutting down the constant error to a minimum. The switch consists of a series of thin brass leaves which

dip into or pass out of pools of mercury when the pendulum passes through its position of rest. A screen (E) with a small slot to allow the light to pass through is placed just back of the pendulum to prevent any stray light from reaching the window in screen H.

The advantage of this pendulum is that it is noiseless, or at least, it does not make sufficient noise during its movement to be perceptible. However, in order to be certain that no sound would reach the subject that might condition him (liminally or subliminally), the pendulum was mounted on hair felt, and then enclosed in a sound-proof box.

Back of the screen H is a heavy table, on the edge of which is mounted an ophthalmometer head rest; 20cm. to the right of the middle position of the head rest, and 33cm. from the edge of the table is the reactor's key. The position of the key (telegraph) allows the subject's arm to rest upon the table. About 50 cm. in front of the head is a telegraph sounder, which is to warn the subject when a series of reactions is going to start. It operates automatically through the control mechanism illustrated in Fig. 6.

The control mechanism is operated from lighting circuit through a vibrating reed located beneath the table top (Fig. 5). It controls the length of the intervals between reactions and the order of presentation and removal of the stimuli. In the belt (A Fig. 6) are five rows of slots. Two of these control the movements of the pendulum, three of them control the order of presentation and removal of the sound. Then there is one other single perforation for operating the sounder at the beginning of the series, and warning the experimenter through the receivers (Fig. 5) that the series is about to begin.

The chronoscope (A, Fig. 5) has the weight removed and is operated by belt by the motor at B.[20] The transmission apparatus has an adjustable friction clutch made of polished brass. By this means the torque exerted on the chronoscope drum is independent of the speed and voltage impressed upon the motor provided the motor is running at a speed greater than is necessary to operate the chronoscope. The reliability of this arrangement for operating the chronoscope has been

[20] This chronoscope was adjusted to operate without springs by Poffenberger and Morgan. *Cf.* A. T. Poffenberger and J. J. B. Morgan, "The Hipp Chronoscope: its use and adjustment," *Jour. Exp. Psych.*, 1:185-199 (1916).

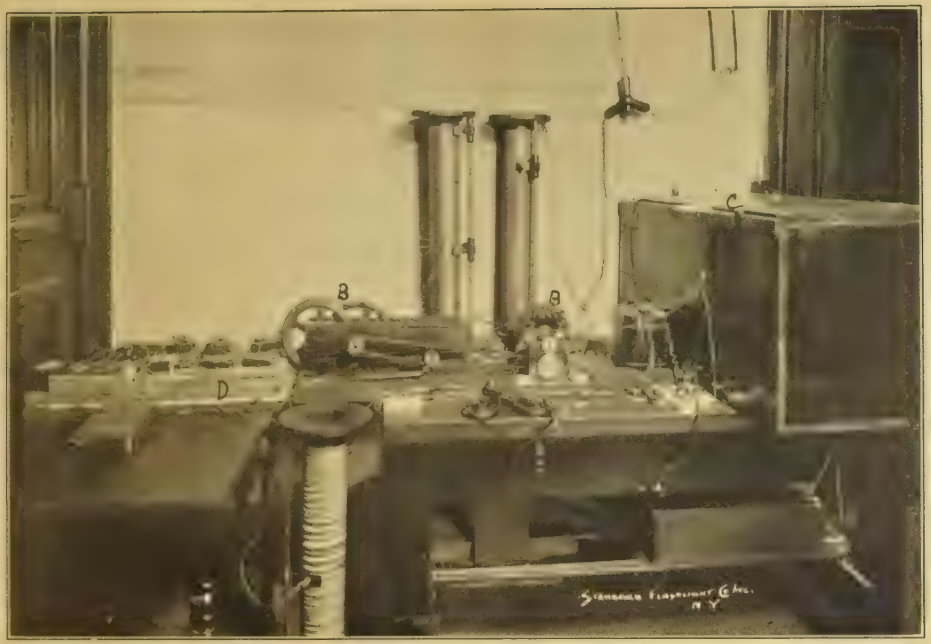

Figure 5. Operator's table and accessory apparatus. (B), Motor and transmission for operating (A) chronoscope. (C), Sound proof box containing stimulus control apparatus. (D), Relays R_m, R_n, Re, Sh, Cu, shown in Fig. 2.

Figure 6.- Stimulus control. (A), belt containing slots through which contact fingers close circuit through electrode (E) to operate relays shown in Fig. 5. (B), large electro-magnet for moving the drum (C). (D), electro-magnet which raises a stop when drum moves, but releases stop before drum has advanced one complete step, thus stopping the drum in the same relative position at every step.

verified periodically with a gravity chronometer. With a setting of 200 milliseconds the chronoscope has given a mean variation at all times of less than one millisecond.

The actual procedure in taking a series of reactions is in brief as follows: The subject is seated upon an adjustable stool with his head resting easily in the head rest, with the receivers on his head. The subject is first told to react to the light when it appears and again when it disappears, and so on, by raising his index finger from the key. Secondly, he is asked to always remove his finger completely from the key. The third instruction is, "Pay no attention to the sound." He is also told that the series of reactions begins, and that the light appears for the first time, just a few seconds after the click of the sounder which is located just in front of him.

All lights are then extinguished in the dark-room, and the door is closed. The control apparatus is then started. The experimenter places the receivers (Fig. 5) on his head, seats himself directly in front of the chronoscope, and the switches are closed for the solenoids of the pendulum, the chronoscope circuit, and the sounder circuit. When the operator hears a sharp click in the receivers, he opens the sounder switch, reverses the receiver switch, and closes the circuit that operates the relays. The series of reactions then begins. The receivers are connected in circuit with relay Sh (Fig. 2). Every time the armature of Sh moves, the operator hears a click in the receivers. The chronoscope is read aloud to an assistant who records the figures as they are read off. A click in the receivers is always recorded before the next reading. The record of these clicks verifies the accuracy of the series and gives a series of checks to facilitate the use of keys for sorting out the reaction-times for the various modes of stimulation.

SECTION IV

Results and Conclusions

In the present study reaction-times were measured for five subjects, three men and two women; 1600 reactions were taken at each sitting, giving a total of 3200 reactions for two sittings, or 400 reactions for each mode of stimulation.[21] The two sittings were taken at about the same time of day on different days. The auditory stimulus was a tone with a frequency of 1024 vibrations and an intensity of 0.9 dynes per cm^2. The visual stimulus was green light with a wave length[22] of 5100 Angstrom units and an intensity of $.32 \times 10^{-8}$ watts/mm^2.

The distributions for the five subjects are presented in tables I—V. At the bottom of each table are given the mean, the median, the standard deviation (SD), the Pearson coefficient of variation (V), and the skewness (Sk)[23] of the distribution. In table VI, the eight different modes for each subject are ranked in order of magnitude for mean, median, SD, coefficient of variation, and skewness.

Reaction-times for darkness are almost invariably quicker than those for the onset of light. The only exception is DQ and LQ for subject E, and in this case they are approximately the same. This is in substantial agreement with the results obtained by Holmes (33). Furthermore, the subjects reported that they believed they were reacting faster to the removal of the light, complaining that they had difficulty in attending when no light was present.

The above result does not necessarily mean that reactions are intrinsically faster for the disappearance than for the appearance of light. An analysis of the conditions of the experiment would lead one to expect the cessation reaction-times to be the shorter. When the light is on, the subject has the lighted window upon which to fixate his eyes, in other words,

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[21] All were unpracticed subjects except subject A. Subject A had had no recent practice; he served as subject for a long series of reactions in 1916. No preliminary practice was given to any of the subjects.

[22] This is the median wave length for a band having a width of *approximately* twenty wavelengths for this region of the spectrum.

[23] $Sk = \frac{3\ (\text{mean}—\text{median})}{SD}$

the presence of the light in this case facilitates adjustment of the "accessory sensory apparatus." While waiting for the light to appear, on the other hand, the subject is shrouded in complete darkness with no definite point to fixate upon (except a possible after-image which moves about with the movement of the eyes). That reaction-times to the appearance and disappearance of light are probably about the same for the same degree of sensory adjustment could be verified by always leaving a small spot of light at the centre of the window for the subject to fixate upon; or the window could be lighted all the time, and the subject instructed to react to a decrease or an increase of intensity.

Difference in degree of adjustment is probably the most plausible explanation of differences between the reaction-times for the presentation and removal of stimuli. If the reaction-times are about the same then the degree of sensory adjustment is about the same. The writer believes this theory will hold even if we grant the truth of one or both the theories of resistance promulgated by Piéron and Sherrington. This is contrary to the view of Woodrow, who believes that disparity between reaction-times to the presentation and removal of stimuli is an inevitable consequence of any theory based upon resistance to be overcome, such as synaptic resistance or the latent, sensory period of the first sensory neurone (*cf.* p. 17). That Woodrow's contention is wrong has been fully discussed on another page and will not be given any further discussion at this point (*cf.* pp. 21-22).

On the other hand, the facilitating effect of the removal of sound is always less than for its presentation. In other words, we have shorter reaction-times to the *removal* of light, but on the contrary, the greatest facilitating effect occurs for the *presentation* of sound (see tables VI and VII). We also have the peculiar result that reaction-times tend to be longer for quiet continuing without change than for sound continuing without change. In other words, the mere presence of the auditory stimulus seems to have a facilitating effect, even though it is continuing without change of intensity (*Cf.* table VII). The facilitating effect, however, of a continuing stimulus is not exhibited in all cases. Subject A gives a relative difference of —.88 for DK:DZ, and subject D gives differences of .52 for LK:LZ, and .96 for DK—DZ.

The fact that the reaction-times seem to be shorter for a continuing stimulus suggests that the mere presence of a stimulus may facilitate *adjustment* for reactions to other stimuli. That it facilitates adjustment is probably a more plausible explanation than the statement that the effect is due to a *summation* of stimuli. The effect may be due to an increase of effort on the part of the subject; in other words, the continuing stimulus (sound) may be a distractor having an effect similar to that observed by Morgan.[24] We would naturally expect summation to occur only where a change takes place in the stimuli; in other words, summation value is a function of change (the changes may occur in rapid succession so that the effect of one has not had time to disappear before the next is presented). Some other relations, however, lead to some interesting queries. If the mere presence of a stimulus facilitates adjustment to react, then reaction-times *caeteris paribus* ought to be shorter for the removal of sound than for its presentation. If, in other words, the stimulation value for the removal of sound is the *same* as that for its presentation, then the *summation effect* due to the removal of the sound plus the *increased efficiency of adjustment* due to the continuance of the sound (just preceding its removal) ought to have a greater total effect than that which would arise from the mere summation effect resulting from the presentation of the sound with the light. But the contrary is true; reaction-times for the combinations LS and DS are consistently shorter than those for the combinations LQ and DQ (*Cf.* table VII). We can explain this in two ways: First, the stimulation value for the removal of sound may be so great that, in spite of the facilitating effect of the mere presence of the auditory stimulus, the *total* effect, nevertheless, is less for its removal than for its presentation. Secondly, facilitation of adjustment to react to light may decrease the summation effect due to the sound. In other words the summation effect may be greater when the subject is poorly adjusted to react. We can state this generally by saying that the summation effect due to changes in extraneous stimuli is inversely proportional to the degree of adjustment to react to a *definite* stimulus.

[24] John J. B. Morgan, "The overcoming of distraction and other resistances," *Arch. of Psych.*, No. 35, p. 28 (1916).

Table VII is a table of relative differences obtained by finding the differences between the mode with quiet continuing without change and the other modes, then multiplying the real difference by 100 and dividing by the mean for the LK or DK. For example, the real difference for subject A for LK-LZ is 14.2. This multiplied by 100 and divided by 168.1 equals 8.44. Inspection of the table shows that the facilitating effect of sound and quiet is relatively about the same for light as for darkness.

We also find certain significant relations of correspondence appearing between the magnitudes of the mean, coefficient of variation, and skewness. The results of all the subjects show a tendency for the mean to increase in magnitude as the coefficient of variation decreases in magnitude. For example, DS is the quickest mode for all the subjects, but its coefficient of variation is the largest for three of the subjects, and stands second and third from the top respectively for subjects B and E (*cf.* Table VI). Stated in another way, the swifter the subject reacts the more irregular he becomes.[25]

[25] This is in substantial agreement with Robert MacDougall (*Cf.* p. 30). Thorndike ("Empirical Studies in the Theory of Measurement," *Arch. of Psych.*, No. 3, p. 9 ff.) has observed that a non-linear relation between central tendency and the Pearson coefficient of variability is a common occurrence in biological measurements.

TABLE I

Frequency distributions of reaction-times of subject A

	Stimulus Combination							
Time	*DS*	*DQ*	*LS*	*DK*	*DZ*	*LQ*	*LZ*	*LK*
70	2	2	11		2			1
80	52	18	37	1	5	4		2
90	64	22	30	3	2	25	2	1
100	80	77	46	14	6	67	11	4
110	44	95	75	29	26	70	29	18
120	34	55	50	20	29	43	48	21
130	35	32	44	37	24	45	72	40
140	24	33	37	66	61	28	53	43
150	13	23	30	71	64	29	61	44
160	10	16	16	49	71	20	30	56
170	12	11	4	30	34	17	19	45
180	11	3	3	14	17	13	21	33
190	9	2	7	17	16	12	16	22
200	4	4	0	13	4	11	12	20
210	3	2	2	10	9	0	6	16
220	1	0	3	4	7	9	8	11
230	2	1	0	5	6	0	5	8
240			3	5	7	3	2	4
250		1	0	2	2	2	0	3
260			2	0	0	0	1	4
270				5	1	1	0	1
280		1		3	2	1	1	2
290				2			0	1
300							2	
310								
320					3			
330								
340					1			
350		2						
360							1	
370								
380								
390								
400								
410					1			
420								
430								
440								
450								
460								
Mean	120.7	126.4	125.3	159.8	161.2	137.2	153.9	168.1
Median	110.4	108.4	110.2	144.2	147.0	117.9	137.2	146.3
SD	32.2	31.7	31.4	36.2	39.3	35.9	34.1	35.6
V	26.7	25.08	20.5	22.65	24.3	26.15	22.15	21.17
Sk	.97	1.70	1.45	1.29	1.10	1.61	1.46	1.84

TABLE II

Frequency distributions of reaction-times of subject B.

	Stimulus Combination							
Time	*DS*	*DQ*	*LS*	*DK*	*DZ*	*LQ*	*LZ*	*LK*
70	0						2	
80	10	1	1	4				
90	0	1	6	0				
100	24	3	7	2	2	2		
110	74	7	13	3	0	2	6	
120	68	17	28	2	2	3		2
130	42	23	44	5	11	8		4
140	46	65	33	14	24	30	2	1
150	39	76	32	32	47	21	2	3
160	42	57	33	52	74	34	5	8
170	16	47	34	58	73	15	12	10
180	4	20	21	42	51	28	32	30
190	6	19	24	34	26	54	33	26
200	9	13	23	16	17	29	40	21
210	7	10	17	22	14	33	43	40
220	2	6	18	28	14	36	35	46
230	2	5	14	16	3	20	36	35
240	2	8	6	12	8	18	31	19
250	0	3	12	10	10	5	25	28
260	3	4	12	5	6	10	17	13
270	0	1	6	10	0	5	14	15
280	0	2	0	6	6	12	12	22
290	1	3	2	4	2	5	9	15
300		1	2	6	4	3	8	14
310		0	3	0	0	2	7	12
320		0	0	2	2	3	8	5
330		4	0	0		1	1	4
340		2	2	0		1	4	2
350		0	1	0		4	2	2
360		1	1	5		2	1	3
370		1	2	2		4	1	2
380			1	2		0	2	4
390			0	2	2	1	2	4
400			0	2	2	1	4	6
410			0	0		2		6
420			0	0		3	2	2
430	2		2	0		1		6
440	0			2		2		
450	1						2	
460	0							
Mean	143.9	171.7	181.6	201.9	186.0	212.4	235.6	251.35
Median	125.7	151.2	160.9	176.6	165.4	191.0	216.5	225.4
SD	41.0	42.2	55.2	55.6	41.0	60.1	54.5	63.0
V	28.49	24.57	30.39	27.53	22.04	28.33	23.13	25.06
Sk	1.33	1.45	1.12	1.36	1.51	1.07	1.05	1.23

TABLE III

Frequency distributions of reaction-times of subject C

	Stimulus Combination							
Time	*DS*	*DQ*	*LS*	*DK*	*DZ*	*LQ*	*LZ*	*LK*
70	0	2	0	4	2	1	1	2
80	3	1	2	1	2	1	1	2
90	1	0	2	3	4	2	1	0
100	8	2	2	1	3	0	2	1
110	14	4	3	1	1	1	2	0
120	32	1	8	4	3	0	2	3
130	44	6	20	6	1	4	4	1
140	45	18	31	8	4	6	3	4
150	43	43	34	15	21	16	7	7
160	31	46	33	24	38	26	9	4
170	29	59	31	60	76	43	25	14
180	23	37	40	47	49	49	28	23
190	26	34	40	31	39	37	44	31
200	14	22	25	28	28	36	49	35
210	16	15	12	28	18	32	38	34
220	9	13	19	12	18	21	29	23
230	11	16	15	9	12	18	25	19
240	7	10	9	14	12	24	19	18
250	7	13	5	15	9	14	13	20
260	1	10	10	11	3	8	12	19
270	4	8	8	10	2	8	14	10
280	5	10	6	8	9	7	8	11
290	2	4	6	10	1	5	8	14
300	6	4	8	8	8	6	3	16
310	3	3	6	4	9	2	11	11
320	1	2	4	5	5	8	4	9
330	3	3	5	6	4	4	7	5
340	3	2	0	2	1	0	4	9
350	0	2	5	2	1	6	6	6
360	2	2	0	2	4	3	1	7
370	1	0	3	4	4	3	3	4
380	3	2	2	1	2	0	1	8
390	1	1	0	3	0	1	6	5
400	0	1	0	2	0	0	1	6
410	1	0	0	7	0	2	4	6
420	1	0	0	0	2	1	0	3
430		2	3	2	1	2	1	4
440		1	2	1	0	2	1	5
450		1	0	1	3	1	2	0
460		0	1		1		1	1
Mean	179.7	202.3	203.5	219.1	208.5	218.8	232.5	256.5
Median	153.2	174.8	178.5	187.7	179.18	193.9	205.8	228.4
SD	59.4	58.0	64.3	69.0	63.1	60.1	64.2	75.4
V	33.05	28.67	31.10	31.49	30.26	27.47	27.61	29.43
Sk	1.33	1.42	1.16	1.37	1.39	1.24	1.24	1.11

TABLE IV

Frequency distributions of reaction-times of subject D

	Stimulus Combination							
Time	*DS*	*DQ*	*LS*	*DK*	*DZ*	*LQ*	*LZ*	*LK*
70								
80								
90	2						1	
100			1	1				
110			1	0				
120		2	1	0	1		1	
130	1			1			1	
140	5	1		1			1	
150	6	2	2	1	1	2	1	
160	14	3	4	0	1			1
170	17	9	7	1	1	1		1
180	40	6	25	2	4	2	1	
190	48	23	41	7	7	6		
200	46	42	43	16	18	20		
210	31	51	57	36	46	23	2	2
220	41	56	49	44	49	42	3	2
230	29	29	32	47	66	45	7	11
240	18	34	26	45	42	44	12	30
250	14	28	23	44	32	37	29	26
260	15	21	15	34	30	26	45	36
270	13	12	11	20	11	27	59	31
280	10	12	11	16	12	19	38	50
290	7	13	8	13	11	21	37	42
300	9	7	6	11	10	16	30	32
310	5	10	9	10	7	15	29	30
320	6	5	4	8	10	13	20	23
330	3	4	6	7	3	3	17	10
340	3	2	2	8	7	7	6	13
350	1	7	1	6	6	6	11	11
360	1	2	3	3	3	4	5	6
370	3	1	1	3	3	5	10	3
380	1	2	1	3	2	5	6	7
390	1	5	1	2	2	2	5	6
400		3	1	2	2	1	3	4
410	3	1	2	4	0	2	3	7
420	3	2	1		4	2	1	6
430	1	1	1	4	6	1	5	3
440		1	1		2	3	3	3
450		1	2		0		3	3
460	3	2	1		1		5	1
Mean	227.5	246.8	236.8	260.7	258.1	266.3	300.5	302.1
Median	206.8	221.72	213.6	239.6	231.4	244.0	279.7	282.4
SD	53.4	54.5	52.3	50.4	45.1	50.6	52.9	50.2
V	23.47	22.82	22.09	19.33	20.96	19.0	17.60	16.58
Sk	1.16	1.38	1.33	1.25	1.48	1.32	1.18	1.17

TABLE V

Frequency distributions of reaction-times of subject E

	Stimulus Combination							
Time	*DS*	*DQ*	*LS*	*DK*	*DZ*	*LQ*	*LZ*	*LK*
70	1					1		
80						1		1
90	1							
100		1	1	1		1	3	
110	1		1		2	2	1	
120	3		3		1	1		
130	7	1	7		1	1	2	
140	19	8	24		2	4	1	
150	24	10	30	2	5	5	2	2
160	24	20	29	2	4	10	3	1
170	21	15	27	5	7	10	7	6
180	36	39	33	10	13	24	10	3
190	45	30	38	12	26	51	14	6
200	39	45	26	27	31	48	37	9
210	28	36	35	24	53	43	45	22
220	27	23	26	32	29	28	35	22
230	31	23	20	28	36	35	34	24
240	15	29	16	27	26	22	38	24
250	23	26	17	22	24	14	27	35
260	13	17	15	19	23	21	35	28
270	5	15	5	26	21	17	22	26
280	6	13	8	24	17	18	15	23
290	4	10	8	18	11	13	18	34
300	4	5	4	16	13	6	11	27
310	7	4	3	17	4	5	10	19
320	3	6	2	14	9	3	4	17
330	1	3	8	12	13	1	3	16
340	1	2	3	11	9	2	6	9
350	2		1	13	1	3	2	3
360	2		1	5	2	1	3	9
370	1	5	2	6	1	1	2	9
380	1	6	1	3	4	2	3	10
390	1	1	1	2	3	2	3	1
400	1		1	4	4	1	1	1
410	2	3	1	5	3		1	5
420				5		2	1	5
430			1	4				1
440	1	1		1			1	1
450			1	2	1			1
460		3	1	1	1	1		
Mean	212.8	231.5	213.3	273.7	249.2	230.4	247.9	281.5
Median	194.6	208.6	192.7	254.2	226.6	209.5	231.6	266.5
SD	52.9	57.8	57.6	63.4	56.8	51.4	50.5	56.9
V	24.86	27.70	27.0	23.15	22.79	22.3	20.37	20.21
Sk	1.03	1.19	1.07	.92	1.19	1.22	.97	.79

TABLE VI

Median, mean, S.D. Coefficient of Variation, and Skewness ranked in order of magnitude for each mode.

M		*Md*		*SD*		*V*		*Sk*	
				Subject A					
LK	168.1	DZ	147.0	DZ	39.3	DS	26.70	LK	1.84
DZ	161.2	LK	146.3	DK	36.2	LQ	26.15	DQ	1.70
DK	159.8	DK	144.2	LQ	35.9	DQ	25.08	LQ	1.61
LZ	153.9	LZ	137.2	LK	35.6	DZ	24.30	LZ	1.46
LQ	137.2	LQ	117.9	LZ	34.1	DK	22.65	LS	1.45
DQ	126.4	DS	110.2	DS	32.2	LZ	22.15	DK	1.29
LS	125.3	LS	110.2	DQ	31.7	LK	21.17	DZ	1.10
DS	120.6	DQ	108.4	LS	31.4	LS	20.50	DS	.97
				Subject B					
LK	251.3	LK	225.4	LK	63.0	LS	30.39	DZ	1.51
LZ	235.6	LZ	216.5	LQ	60.1	DS	28.49	DQ	1.45
LQ	212.4	LQ	191.0	DK	55.6	LQ	28.33	DK	1.36
DK	201.9	DK	176.6	LS	55.2	DK	27.53	DS	1.33
DZ	186.0	DZ	165.4	LZ	54.5	LK	25.06	LK	1.23
LS	181.6	LS	160.9	DQ	42.2	DQ	24.57	LS	1.12
DQ	171.7	DQ	151.2	DZ	41.0	LZ	23.13	LQ	1.07
DS	143.9	DS	125.7	DS	41.0	DZ	22.04	LZ	1.05
				Subject C					
LK	256.5	LK	228.4	LK	75.4	DS	33.05	DQ	1.42
LZ	232.5	LZ	205.8	DK	69.0	DK	31.49	DZ	1.39
DK	219.1	LQ	193.9	LS	64.3	LS	31.10	DK	1.37
LQ	218.8	DK	187.7	LZ	64.2	DZ	30.26	DS	1.33
DZ	208.5	DZ	179.1	DZ	63.1	LK	29.43	LZ	1.24
LS	203.5	LS	178.5	LQ	60.1	DQ	28.67	LQ	1.24
DQ	202.3	DQ	174.8	DS	59.4	LZ	27.61	LS	1.16
DS	179.7	DS	153.2	DQ	58.0	LQ	27.47	LK	1.11
				Subject D					
LK	302.1	LK	282.4	DQ	54.5	DS	23.47	DZ	1.48
LZ	300.5	LZ	279.7	DZ	54.1	DQ	22.82	DQ	1.38
LQ	266.3	LQ	244.0	DS	53.4	LS	22.09	LS	1.33
DK	260.7	DK	239.6	LZ	52.9	DZ	20.96	LQ	1.32
DZ	258.1	DZ	231.4	LS	52.3	DK	19.33	DK	1.25
DQ	246.8	DQ	221.7	LQ	50.6	LQ	19.00	LZ	1.18
LS	236.8	LS	213.6	DK	50.4	LZ	17.60	DS	1.16
DS	227.5	DS	206.8	LK	50.2	LK	16.58	LK	1.17
				Subject E					
LK	281.5	LK	266.5	DK	63.4	DQ	27.70	LQ	1.22
DK	273.7	DK	254.2	DQ	57.8	LS	27.00	DQ	1.19
DZ	249.2	LZ	231.6	LS	57.6	DS	24.86	DZ	1.19
LZ	247.9	DZ	226.6	LK	56.9	DK	23.15	LS	1.07
DQ	231.5	LQ	209.5	DZ	56.8	DZ	22.79	DS	1.03
LQ	230.4	DQ	208.6	DS	52.9	LQ	22.30	LZ	.97
LS	213.3	DS	194.6	LQ	51.4	LZ	20.37	DK	.92
DS	212.8	LS	192.7	LZ	50.5	LK	20.21	LK	.79

TABLE VII

Relative differences between quiet continuing without change and the other modes

Subj.	*A*	*B*	*C*	*D*	*E*
LK–LZ	8.44	6.24	9.35	.52	11.93
LK–LQ	18.38	15.47	14.69	11.18	18.15
LK–LS	25.46	27.73	20.66	21.61	24.22
DK–DZ	—.88	7.87	4.84	.96	8.98
DK–DQ	20.90	14.95	7.21	5.33	15.42
DK–DS	24.53	28.72	17.66	8.89	22.25

The relative differences are obtained by finding the differences between the mode with quiet continuing without change and the other modes, then multiplying the real difference by 100 and dividing by the mean for LK or DK. That is:

$$\frac{\text{(real diff. between LK or DK and the other combinations) (100)}}{\text{mean of LK or DK}}$$

TABLE VIII

Rank correlations between the two averages M and Md and the coefficients of variation and skewness

	M:V	M:Sk	V:Sk	Md:V	Md:Sk
Subj. A					
P.	—.44	+.31	—.30	—.21	—.11
P. E.	.20	.20	.23	.24	.25
Subj. B					
P.	—.113	—.5	—.33	—.33	—. 5
P. E.	.25	.19	.22	.22	.19
Subj. C					
P.	—.4	—.47	+.15	—.54	—.54
P. E.	.21	.19	.24	.18	.18
Subj. D					
P.	—.97	—.38	+.41	—.96	+.21
P. E.	.0015	.21	.21	.08	.24
Subj. E					
P.	—.57	—.51	+.43	—.76	—.61
P. E.	.17	.19	.20	.11	.16

In the case of subjects B, C, D, and E, there is a tendency for the mean and skewness to vary inversely. Subject A, however, gives a small positive correlation between the mean and skewness. In Table VIII is given a summary of a series of rank correlations for each subject for the mean and coefficient of variation (M:V), the mean and skewness (V:Sk), the coefficient of variation and skewness (V:Sk), the median and the coefficient of variation (Md:V), and the median and skewness (Md:Sk). The correlations in most cases are too low to be significant.

The form of the distributions suggests that the normal curve is probably a bad fit for these reaction-time distributions, and if we assume that the causes are many, we cannot explain the variation from normalcy as due to inequality between p and q (where p and q stand for the relative number of successes and failures due to the combined operation of the various causes), because a skew curve of this type approaches very closely to the normal Gaussian form for a large number of causes. This suggests that the relation between cause and effect is non-linear, and that the distributions are generated by causes whose effect is dependent upon magnitude. In other words the causes are not independent; the effect of one factor is not independent of the effects of other factors. We can put this in another way by saying that the size of the deviations is dependent upon the magnitude of the variate. The matter can be put in this way: the effect of a given factor upon a given value of x is not the same as it would be for any other value of x. This is the reverse of what is true for the normal curve, in which the effect of a given factor is the same for all values of x. If the causes produce effects which are proportional to the size of the variate, then the resultant effect is a logarithmic function of the number of causes. This gives us the logarithmic curve of frequency.

A few other types of curves were applied to some of the distributions in the hope of finding a clue to a better fitting curve of error for reaction-time data. Some of the statistical constants and the chi-square test of goodness of fit have been computed for various laws of error, and tabulated in Tables IX to XII, inclusive. These results were not intended to be exhaustive, but only tentative and suggestive of further work in the same direction. It was hoped that they might furnish evidence leading to a more satisfactory law of error for reaction-time distributions,—a frequency curve which would not only give a more adequate description of the data, but which at the same time would be flexible and simple to apply in practice. Secondly, it was hoped to lead to a curve with a simple logical basis, rather than to one which would merely give an empirically good fit. A curve with a logical basis would tend to suggest an hypothesis concerning the nature of the relation existing between the causes operating and the effects produced.

This study was limited to distributions DS of subjects A, B, and C, the most extensive investigation being made on that of subject A. In the latter case not only is the AD and SD calculated about the arithmetic mean, but also the AD and SD of the deviations above and below the mean, thus giving two dispersion ratios of the same kind for the same mean. Fitting curves to data by this method involves the use of two equations, one for the portion of the distribution above the mean, and one for the portion below the mean. In the present case, the method gives no appreciable improvement in fit (*cf.* Table XI). Even if the fit were fairly good, the apparent awkwardness of the method would make it unsuitable to use in practice, and the curves would be very difficult to interpret due to the lack of a unitary logical basis for their formation.

In the case of the normal curve (Laplace's second law), the frequency of a deviation is an exponential function of the square of the error. If, on the other hand, the frequency of a deviation is an exponential function of the absolute value of the error, we have what is known as the median law of error (Laplace's first law), the equation of which is,

$$y = \frac{N}{2\theta} e^{-\frac{|x|}{\theta}}$$

where θ is the mean deviation about the median. The goodness of fit of the median law is little better than that of the normal curve.

By introducing other powers of x, we can fit an entire family of exponential curves to a frequency distribution. This fact led Rider[26] to introduce a generalized law of error in which the frequency of an error is expressed as an exponential function of the mth power of the absolute value of of the error. This leads to the following equation:

$$y = \frac{Nmk^{1/m}}{\Gamma 2\,(^{1}/_{m})} e^{-k|x|^{m}}$$

The exponent m (which may be a fraction) is determined from the first and second moments of the distribution. This law on account of its generality will *probably* give *in most cases* a more accurate description of the data than the first or second laws, but probably it will not become very useful as a general tool in the treatment of data: first, because of the great amount of labor necessary for its execution; secondly, because it introduces another constant which cannot be easily

[26] Paul R. Rider, "A generalized law of error," *Jour. Am. Stat. Ass'n*, 19: 217-220.

combined with constants of the same kind from other distributions.

The harmonic law of error gives a better fit than either the median or normal laws. This is probably due to the fact that the harmonic law gives us a skew frequency curve. The best fit, however, sems to be given by the logarithmic (geometric) law of error. The equation of the logarithmic curve is,

$$y = \frac{N}{\sigma\sqrt{2\pi}} \frac{Mod}{x} e^{-\frac{\log^2 x}{2\sigma^2}}$$

This curve is easy to apply in practice, and the relative frequencies can be read off from the existing tables of the probability integral.

An attempt was also made to fit the logarithmic normal curve with a change of origin, a move which resulted in a considerable improvement in fit. For subject A, the first trial was taken at 60. This not only resulted in an improvement in fit, as shown by the chi-square test, but the mean was reduced to nearly the same value as the median. By placing the origin at 70, the fit was still further improved, so that the geometric mean nearly coincided with the median. A little reflection will show that an improvement in fit due to a shift of the origin is what we should naturally expect, because there must be a physiological limit to the speed of reaction on the part of a subject at the time the series is taken. In other words, leaving aside the fact that a subject's physiological condition may change from day to day, it must take a certain minimum time for the sensori-motor apparatus to do its work. This would constitute an undisturbed region within which no deviations ever occur. Since the frequency curve only applies to the region of disturbance, the mathematical zero must be at the physiological limit; i.e., at that point below which no reaction-times ever occur. If the logarithmic curve of error is the correct one to apply to reaction-time data, we have an indirect means of ascertaining the physiological limit for reaction-time.

A study of the frequency curve, furthermore, furnishes us with a working hypothesis concerning the operation of the causes by which the distribution is regulated. Here the logarithm of the frequency is a quadratic function of the logarithm of the error. Since the frequency of the logarithms of the reaction-times is normal, it follows that the causes tending

to produce reaction are logarithmic functions of the time it takes to react. In other words, the dominant causes of response on the part of the subject produce effects which are proportional to the time it takes to respond. If we let *degree of adjustment* stand collectively for the causes, then the logarithm of the time is inversely proportional to the degree of adjustment, or

$$J \log (t - p) = C$$

where J is degree of adjustment, t is the reaction-time, and p is the physiological limit.

TABLE IX

Means, dispersions, and other statistical constants for distribution DS of subject A

	Arithmetic	*median*	*logarithmic origin at 0*	*logarithmic orig. at 60*	*logarithmic orig. at 70*	*reciprocal*	*geometric orig. at 0*	*geometric orig. at 60*	*geometric orig. at 70*	*Harmonic*
average	120.7	110.4	2.068007	1.722548	1.620484	.00879622	116.9	52.79	41.73	113.68
σ	32.2		.10634411	.2554231	.2765187	.00201889				
σ_1	23.51									
σ_2	42.06									
Δ	25.49									
Δ_1	21.07									
Δ_2	32.27									
Θ		24.32								
Θ_1		14.05								
Θ_2		34.6								
Fmax	120.7	110.4	2.068	1.722	1.620	.0096416	110.14	37.35	27.82	103.72
$\pm\sigma$ range	88.7—		1.961—	1.467—	1.344—	.0068—	91.5—	29.31—	22.07—	92.5—
	152.9		2.174	1.978	1.897	.0108	149.4	95.05	78.89	147.6
middle 68%		91.56 to 150.8								
v_2	9.73×10^2									
v_3	36.44×10^3									
v_4	510.9×10^4									
B_1	1.442									
B_2	5.397									
K_1	.468									
K_2	3.1464									

Note: σ_1 and σ_2 are the standard deviations of the deviations below and above the arithmetic mean; Δ = mean deviation, Δ_1 and Δ_2 are the means of the deviations, respectively, below and above the arithmetic mean; Θ = mean deviation about the median; Θ_1, and Θ_2 are the means of the deviations respectively below and above the median; Fmax = calculated mode; v_1 v_2 v_4 = second, third, and fourth moments about the mean; and B_1, B_2, K_1, K_2 = constants used as criteria in fitting the Pearson family of curves (cf. Kelley, P. 126).

TABLE X

Statistical constants for distribution DS of subject B.

	arithmetic	*median*	*geometric orig. at O*	*geometric orig. at* 70
average	143.9	125.7	139.69	65.86
σ	41.0			
$\pm\sigma$ range	102.9— 184.9		110.7— 176.2	41.5— 104.5
middle 68%		114.0— 167.1		
Fmax	143 9	125.7	132.34	53.20

TABLE XA

Statistical constants for distribution DS of subject C.

	arithmetic	*median*	*geometric orig. at O*
average	179.7	153.2	171.63
σ	59.4		
$\pm\sigma$ range	120.3— 239.1		102.5— 229.7
middle 68%		131.4— 227.8	
Fmax	179.7	153.2	157.47

TABLE XI

Calculated distributions and chi-square tests for distribution DS of Subject A

		Normal law					Geometic law										
Time	observed frequency f	for σ f_1	for σ_1 f_2	for σ_2 f_3	Median f_4	Harmonic law f_5	origin at 0 f_6	origin at 60 f_7	origin at 70 f_8	$(f_1-f)^2/f_1$	$(f_2-f)^2/f_2$	$(f_3-f)^2/f_3$	$(f_4-f)^2/f_4$	$(f_5-f)^2/f_5$	$(f_6-f)^2/f_6$	$(f_7-f)^2/f_7$	$(f_8-f)^2/f_8$
0					1								1				
10					2								2				
20		1			3					1			3				
30		1			4					1			4				
40		3			6					3			6				
50		6	2		8		1			6	2.0		8		1.0		
60		11	4		13	1	6	1		11	4.0		13	1.1	6.	1.	
70	2	18	10		19	13	17	19	5	14.22	6.4		15.2	9.3	12.6	15.2	1.8
80	52	27	22		39	37	33	48	44	23.15	72.2		4.3	6.1	22.09	.3	1.4
90	64	36	37		44	60	48	60	71	21.77	19.7		9.1	.26	5.33	.2	.6
100	80	44	54		66	67	56	58	69	29.45	11.5		2.9	2.52	3.49	8.3	1.7
110	44	49	66		68	59	56	49	55	.8	7.3		8.4	3.8	2.57	.5	2.2
120	34	50		38	45	47	50	39	42	.72		.4	1.8	3.59	5.12	.6	1.5
130	35	43		34	30	34	41	30	30	1.48		0	.8	.03	.9	.8	.8
140	24	37		33	20	24	31	23	22	4.56		2.4	.8	.0	1.58	0	.2
150	13	28		27	13	17	22	17	16	8.04		7.2	0	.94	3.68	1	.5
160	10	19		22	9	12	15	13	12	4.36		6.5	.1	.33	1.66	.7	.3
170	12	12		16	6	8	10	10	8			1.0	6	2.0	.4	.4	2
180	11	7		12	4	6	6	7	6	2.3		.1	12.2	4.16	4.16	2.3	4
190	9	4		8	3	4	4	6	4	6.25		.1	12	6.25	6.25	1.5	6
200	4	2		5	2	3	2	4	3	2.0		.2	2	.33	2.0	0	.3
210	3	1		3	1	2	1	3	3	4.0		0	4	.25	4.0	0	0
220	1			2	1	2	1	3	2			.5	0	.5		1.3	.5
230	2			1		1	1	2	1			1.0		1.0	1.0	0	1
240					1	—		2					1			2	
250						—		1								1	
260						—											
270						—											
280						—											
290						—											
300						—											
310						—											
320						—											
330						3								3.0			
340																	
Σ	400									145.10	123.1	19.4	117.6	45.46	83.83	38.1	25.8

TABLE XII

Calculated frequencies for distribution DS of subjects B and C.

	Subject B					*Subject C*		
		Geometric law						
	observed frequency	*origin at* 0	*origin at* 70	$(f_1-f)^2$	$(f_2-f)^2$	*observed frequency*	*Geometric law orig. at* 0	$(f_1-f)^2$
Time	f	f_1	f_2	f_1	f_2	f	f_1	f_1
0								
10								
20								
30								
40								
50								
60		1						
70		3		13.3			1	1.0
80	10	8	2		3.5	3	4	.2
90	0	18	16			1	8	6.1
100	24	30	38	1.2	5.1	8	12	1.3
110	74	43	54	22.3	7.4	14	19	1.2
120	68	49	58	7.3	1.7	32	24	2.6
130	42	50	53	1.3	2.3	44	29	7.7
140	46	47	44	0	.1	45	32	5.2
150	39	40	35	0	.5	43	33	3.
160	42	32	27	3.1	8.3	31	33	.1
170	16	24	20	2.6	.8	29	31	.1
180	4	18	15	10.8	8	23	28	.9
190	6	13	11	3.7	2.3	26	25	0
200	8	9	8	0	.1	14	22	3.
210	7	6	6	.1	.1	16	19	.5
220	2	4	4	1	1	9	16	3.
230	2	3	3	.3	.3	11	13	.3
240	2	2	2	0	0	7	10	.9
250	0	—	2			7	8	.1
260	3	—	1			1	7	5.1
270	0	—	1		.3	4	6	.6
280	0	—	—			5	4	.2
290	1	2	—	2		2	3	.3
300			—			6	3	3.
310			2			3	2	.5
320						1	2	.5
330						3		
340						3	..	..
350						0	..	..
360						2		..
370						1	..	..
380						3		.. .9
390						1	..	..
400						0	.. 7	..
410						1	..	..
420						1	..	..
Σ	400			69.0	42.1			57.4

SUMMARY

1. Reaction-times to darkness tend to be shorter than those to light.
2. The onset of quiet usually facilitates less than the onset of sound.
3. The facilitating effect of sound and quiet is *relatively* about the same for light as for darkness.
4. Reaction-times for both light and darkness are shorter when the sound continues without change.
5. There is a slight tendency for the mean to increase in magnitude as the coefficient of variation decreases in magnitude.
6. There is a small negative correlation between the average and the amount of skewness.
7. There is a low negative correlation between the coefficient of variation and skewness.
8. The logarithmic curve of error will probably give a better description of the data than the normal law. Its use suggests the following:
   A. There is a physiological limit below which no deviations occur. The use of the logarithmic law furnishes an indirect method of determining the physiological limit.
   B. The form of the frequency curve gives us some insight into the relation existing between the causes and the effects they produce. If we let *degree of adjustment* stand for the causes taken collectively, then

$$J \log (t - p) = C$$

   where J is degree of adjustment, t is the time, and p is the physiological limit.

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